PEAT SLIDES: MORPHOLOGY, MECHANISMS AND RECOVERY

By

Andrew James Mills

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Department of Geography
University of Durham
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ABSTRACT

This thesis investigates the morphology, mechanisms and recovery of peat slide failures using a combined field and laboratory approach. Detailed field investigations are based in the North Pennines, Northern England. The North Pennine regional sample is compared with a global database of peat mass movements, compiled from literature sources and field survey in the UK and Ireland. The database identifies two major types of peat mass movement, peat slides and bog bursts. Both types have been reported in documentary sources during the last 300 years, although peat slides appear to be increasing in frequency. Peat slides occur at higher altitudes and on steeper slopes than bog bursts.

Previous studies of peat slides have suggested a translational failure mechanism, with a failure plane at or below the peat-substrate interface. Investigations in the North Pennines identified 14 failures spanning the last 68 years, of which four are previously undocumented. All show similar characteristic features including: excavated crescentic-linear failure scars, rafted and/or blocky debris and widespread deposition of slurry. Sedimentation patterns suggest a rapid and progressive transition from slide to flow, with localised extensive and compressive movement. Peat slurry comprises the largest volume of transported material. Laboratory investigation of materials at each site suggest that the peat-substrate zone was the most likely plane of failure in all cases. The irregular nature of this contact zone promotes pockets of weak material, prone to sub-horizontal fracture in the peat mass and low shear strengths in the substrate.

A chronosequence approach is applied to investigate the rate of recovery of the slide scars after failure, by comparing the nature of vegetation assemblages on six North Pennine peat slides of various ages. Initial regrowth of vegetation is slow (1-5 years), with reworking of the exposed substrate by fluvial processes. Thereafter, revegetation progresses at a broadly linear rate (5-50 years). Physical rather than chemical changes in substrate character aid revegetation. The field evidence suggests the process of recovery is completed within 70 years. This partly explains the difficulty of identifying older documented sites. Sediment budget analysis applied to the slide events and to their post-failure development demonstrates that the event phase yields the greatest volume of sediment (between 48 and 96% of the overall budget). Overall, peat slides represent a minor component in the geomorphological activity of the North Pennine region (0.02 – 1.00%).

Because of the bias toward peat slides, a case study of the Glendun (Ireland) bog burst was undertaken to justify the treatment of peat slides and bog bursts as separate event types. This indicated that bog bursts show differing patterns of sedimentation to peat slides, with less vertical erosion, and more elongated peat raft forms. Vertical variations in material properties show wetter, less dense and slightly more humified peat at depth, with a failure zone within the peat mass. The greater quantities of peat that remain allow more rapid revegetation, and impede the development of surface drainage. Consequently, recovery of bog burst scars may be more rapid than for peat slide scars.

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I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this, or any other University. In all cases, where it is relevant, material from the work of others has been acknowledged.

Signed: ....

Date: ....

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CHAPTER ONE INTRODUCTION

1.0 Scope of chapter

This thesis is concerned with the nature of shallow mass movements in peatlands, specifically those in upland blanket mire areas of the North Pennines of England. While the study of coastal landslides in the UK has dominated recent mass movement research, inland landslides have received less attention (Jones and Lee, 1994). Inland mass movements are often viewed as either small in scale, or relicts of past climates in which geomorphological processes were more active (Jones and Lee, 1994). However, as this thesis will show, peat landslides can be of considerable scale, be highly disruptive in the environments in which they occur, and are the most severe geomorphological events acting in peatlands. Traditionally, mass movement studies have been validated with reference to socio-economic factors, such as loss of life, loss of land and loss of infrastructure (Crozier, 1986; Brabb and Harrod, 1989). Peat mass movements are, however, isolated events in sparsely populated environments. The extent to which they are significant relates to the effect they have on peat blanket stability. Given the high landscape value increasingly afforded to peat areas (e.g. Taylor, 1983; Charman, 2002), an understanding of their causes and consequences is important in the conservation and preservation of peatlands. This viewpoint is embodied in the aims and scope of this thesis.

This chapter introduces the subject of peat mass movements, and outlines the scope of the thesis. Section 1.1 briefly describes blanket peat catchments and their importance. Section 1.2 outlines the nature of existing research undertaken on peat mass movements. Section 1.3 states the research aims and general objectives of this study, and section 1.4 provides a brief outline of the thesis structure.

1.1 The nature of blanket peat catchments

Peat is a term used to describe many organic soils. These may range from coarse-fibre, woody meshes of partly decomposed floral material to amorphous, almost liquid muds with no visible floral remnants (Landva *et al.*, 1983). Generally, soils are classified as 'peat' when the organic content exceeds 60% (Akroyd, 1964). Most of the organic material is partially decomposed. Peat soils in their natural setting are very wet, commonly 90-95% water by mass (Hobbs, 1986). This reflects the setting in which peat accumulates, in waterlogged areas and under humid climatic conditions.

Globally, there are an estimated four million square kilometres of peatland, over 90% of which lie in the northern hemisphere (Maltby and Proctor, 1996). In the United Kingdom and Ireland, where the majority of peat mass movements are reported, blanket peat represents a significant proportion of the overall peat deposit (Tallis *et al.*, 1997). Blanket peat may develop over flat and sloping ground (up to 25°) so long as climatic and drainage conditions are appropriate, and the ground surface is sufficiently moist. The degradation of blanket peat by anthropogenic and natural causes has both environmental and economic significance. Blanket peat areas are significant in terms of land-use, in particular for sheep grazing, game management and peat extraction for fuel (Taylor, 1983), and as wilderness landscapes (Tallis *et al.*, 1997). They also provide distinctive habitats for a variety of specialized flora and associated fauna (Rodwell, 1991). In the context of this geomorphological study, upland peatlands are important hydrologically, and are active erosion and deposition environments which may have local, regional and natural significance in carbon recycling.

In recent years, a greater significance has been attached to peat deposits as global carbon stores. Immirzi *et al.* (1992) estimate the pre-disturbance mass of fixed carbon in world peatlands at between 329 and 528 Gt, which amounts to over 20% of the carbon stored in world soils, and an amount equivalent to that held in the atmosphere (Clymo *et al.*, 1998). Peat degradation, mainly through human induced activity (Wheeler, 1996; Charman, 2002) has been regarded as significant in the loss of this terrestrially stored carbon. However, such losses are poorly quantified.

1.2 Peat erosion and mass movement research in blanket peat catchments

The study of peatland geomorphology often assumes a regional approach (e.g. Pearsall, 1956; Radley, 1962; Slater *et al.*, 1980; Jequel and Rouve, 1983). Such studies investigate the erosion of former intact, gently undulating or planar peat surfaces into increasingly complex patterns, by the action of water, wind and frost. Notable geomorphological investigations of UK peat deposits at the regional scale include those of Tallis (1964, 1965, 1973, 1975), for the south Pennines, and Bower (1960, 1961, 1962) for the south and north Pennines. Regional studies in Ireland have been conducted at a less specific level by Tomlinson (1979, 1981), Cruickshank and Tomlinson (1990) and Bradshaw and McGee (1987).

Process-based studies have considered the export of peat by fluvial and aeolian processes. This has included fine particulate peat export from the walls of pipes (e.g. Gilman and Newson, 1980), suspended sediment yields (Labadz *et al.* 1991) mechanisms and rates for fluvial transport of peat blocks (Evans and Warburton, 2001), the deflation of bare peat surfaces by wind (Warburton, *in press*) and mass movements (e.g. Sollas *et al.*, 1897; Crisp *et al.*, 1964; Carling, 1986). The latter forms the basis of this thesis.

Studies of peat landforms have mainly focused on the development of gully systems, and the relationship between gully patterns and local controls (Bower, 1960; Radley, 1962; Mosley, 1972; Wishart and Warburton, 2001). Peat mass movement studies have been almost exclusively based on description of form, usually employing mapping to describe morphology. Modelling approaches have attempted to predict failure conditions, but have only superficially considered material characteristics (Carling, 1986; Hendrick, 1990; Dykes and Kirk, 2001).

1.3 Research objectives and scope of thesis

Peat mass movements are relatively widely documented, both as features of geomorphological interest, and as features peculiar to peatland environments. A proliferation of terminology, and in some cases, mythology, is attached to their occurrence. Although there is much information available, very little has been synthesised, and almost all reports published focus on specific case studies. The initial objective of this thesis is a synthesis of published work on mass movements in peat environments. The distinction between peat and organic soils is important in determining the scope of such an assessment, and is considered in the following chapter, with subsequent discussion focusing on the characteristics of peatlands.

The second objective concerns the key issue of mass movement classification. Existing terminology uses terms such as 'bog burst', 'bog flow' and 'peat slide', which are used to refer to different characteristic morphologies, and often with implication to differing processes. The justification for this differentiation has been poorly defined, and requires careful reappraisal.

The third objective is to refine our understanding of 'peat slides', through study of morphology and mechanism. Geomorphological form and process are studied in detail for a set of failures classified as 'peat slides' in the published literature (Hudleston, 1930; Crisp *et al.*, 1964; Carling, 1986; Johnson, 1992; Warburton and Higgitt, 1998), and located in the blanket peat of the North Pennines. The majority of previously published case studies have been descriptive rather than analytical, and the major empirical drive of the thesis attempts to readdress this.

The final objective evaluates the landscape significance of peat slides in blanket peat environments. While peat mass movements are frequently recorded, their significance is rarely discussed, possibly because they occur in relatively isolated landscapes where economical and social impacts are relatively minor. The impact of peat slides on upland environments forms the basis of this part of the thesis.

1.4 Thesis structure

Figure 1.1 illustrates the thesis structure. Chapter 2 evaluates existing sources concerning peat mass movements and blanket peat environments. It describes the formation of blanket peat and the spatial distribution of UK, Irish and global peat deposits. The nature of eroding peat systems is outlined, with particular reference to the UK and the main field study area of the North Pennines. The morphological characteristics of peat mass movements are described and evaluated, and their distribution throughout the world's peatlands is documented. The material basis for peat slide and bog burst mechanisms is considered in the light of wider hillslope stability studies. Particular attention is paid to the morphological and mechanistic distinction between peat slides and bog bursts. The temporal significance of peat failures is contextualised within issues of landscape sensitivity, particularly with respect to geomorphological and ecological systems. The second part of the chapter examines gaps in knowledge demonstrated in the literature review. A framework for resolving inconsistencies identified in the peat slide literature is discussed with reference to proposed field and laboratory work.

Chapter 3 substantiates the classification of peat failures provided by Chapter 2 with a quantitative assessment of peat slide and bog burst attributes. This is achieved through exploratory analysis of a global database compiled from literature and field sources. Form, material and geo-ecological attributes are considered under the banners of morphometry, morphology, drainage, material and post-failure development. Hypotheses specific to slide and burst morphology, mechanism and recovery are generated. These are considered in the light of the literature review, and used as a basis for analyses in subsequent chapters.

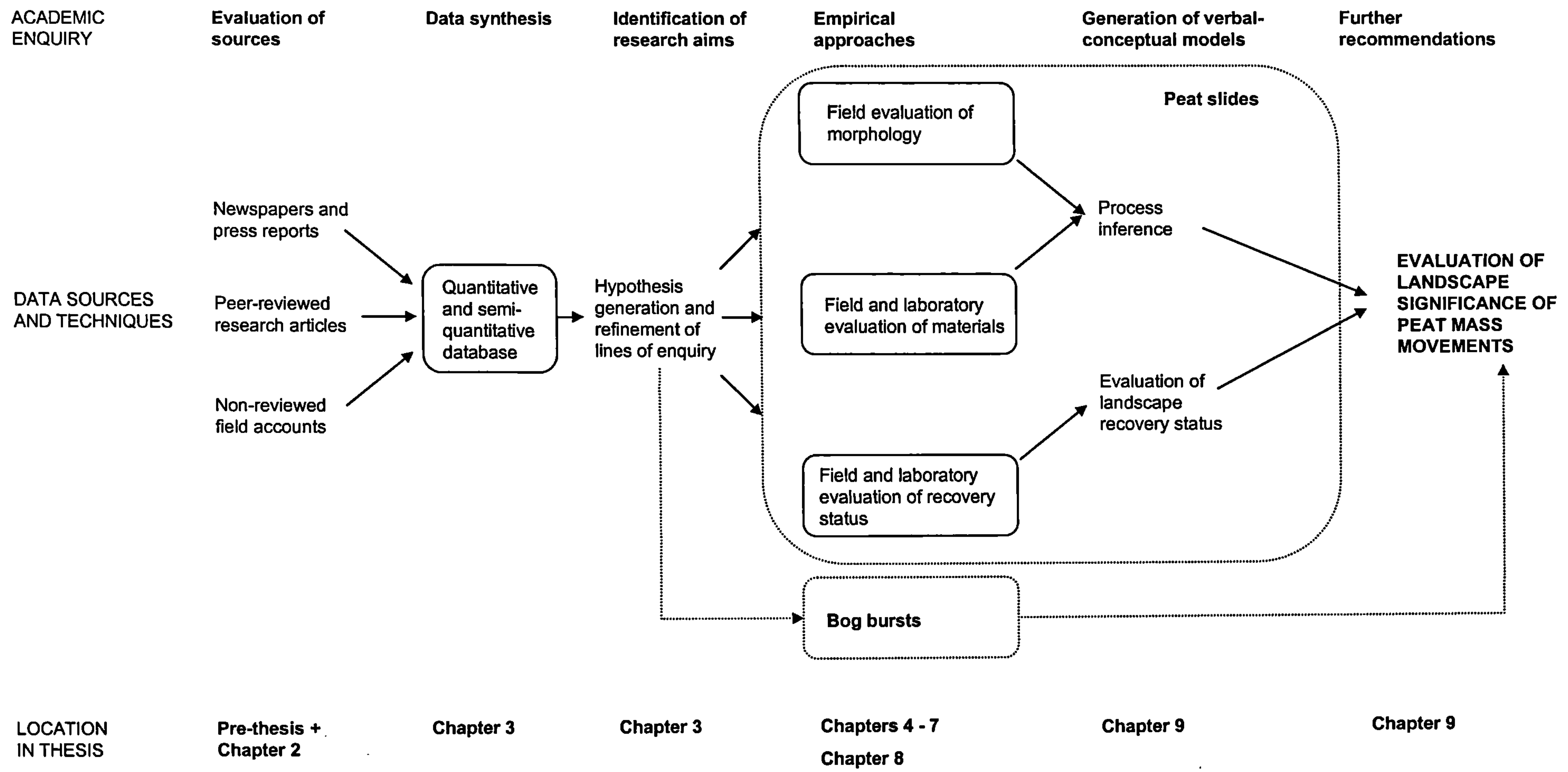


Figure 1.1. Forms of academic enquiry, methodological approach and thesis structure for the evaluation of peat mass movement morphology, mechanism and recovery.

Chapters 4 to 7 comprise empirical approaches to a regional set of peat slides in the North Pennines. Chapter 4 investigates their morphological features. The individual study sites are introduced using geomorphological maps. Morphometric and morphological characteristics of the scar and deposit are characterised and defined in the aftermath of failure and deposition. Slide-characteristics are defined and a morphological-conceptual model is produced for North Pennine peat failures.

In Chapter 5, the dynamics of the dominant peat slide elements are considered. Mode of transport and patterns of deposition are summarised by deposit type. Rafts and blocks are considered as related but distinct components of a continuum of sedimentary deposits. Discussion of peat slide sediment dynamics uses a morphological-conceptual model to produce a process-based explanation of peat slide runout.

Chapter 6 examines the material characteristics of failed peat masses. Layer properties of the peat mass, its substrate and the contact between the two are described and evaluated for all North Pennine peat slide examples. Point properties and engineering behaviour are evaluated for the Hart Hope failure, and related to layer properties. These layer properties are used as a means of comparison across all North Pennine failures, and for the assessment of locally weak horizons in peat and substrate. Previous theories of peat mass stability are tested against these properties. The material basis for a distinct peat slide mechanism is evaluated.

The aftermath of peat slide failure is considered in Chapter 7. The geomorphological, ecological and pedological development of peat slide scars is considered against a backdrop of wider peat blanket evolution for a sub-set of failures of differing age in the North Pennines. A model of scar development within the landscape is proposed.

A comparative bog burst case study is utilised in Chapter 8, in which the Glendun bog burst, Northern Ireland, is described. Peat slide and bog burst morphology, mechanism and recovery are compared. The justification for previously assumed differences between the two mass movement types is evaluated.

Chapter 9 draws together the investigations of previous chapters to consider the causes, characteristics and consequences of peat slides within the blanket peat environment. The significance of slide failures is examined within the nested spatial and temporal frameworks defined previously. The role of peat slides as geomorphological agents is evaluated against other peat erosion processes.

Recommendations for further research are presented, particularly with reference to the clarification of bog burst type failures.

2. MASS MOVEMENTS IN BLANKET PEAT ENVIRONMENTS

2.0 Scope of Chapter

This chapter comprises two main parts. The first reviews existing research into peat landslides, and places this work in the context of global peat environments. The second utilises this information in a framework for the investigation of peat slide failures in the North Pennines. The review describes the current state of knowledge regarding blanket peat systems, with particular reference to their geomorphology, ecology and hydrology. It begins by considering the formation of peat and the distinctive physical properties of peat deposits. This provides a context for description of the spatial and temporal distribution of peat landslides, globally and within the UK. Peat mass movements, in particular peat slides and bog bursts, are then examined as distinct but related form and process types, and contextualised with other erosion mechanisms in blanket peat. Peat mass movements are viewed as part of a spectrum of mass-wastage processes. Established theories of failure mechanisms for peat slides and bog bursts are reviewed. The recovery of peat landslide scars and the relevance of this for long-term landscape sensitivity in these locations is discussed. Finally, the methodological framework is defined with which to address gaps in knowledge associated with peat mass movements.

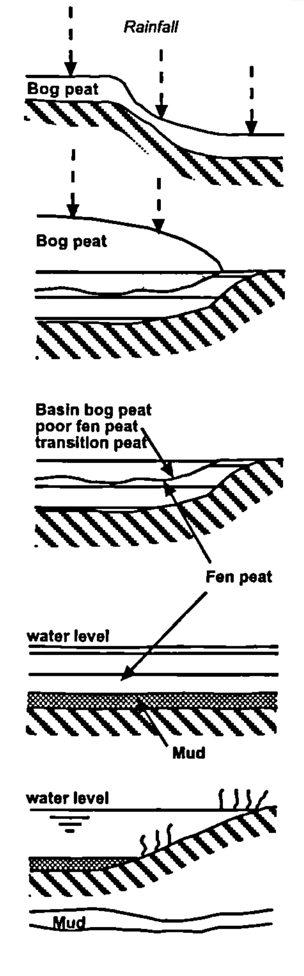
2.1 Introduction to Part One: Blanket Peat Formation In Upland Environments

Peat mass movements have been documented in a variety of peatland settings, from upland to lowland, and from hillslopes to coastal marshes. The physical characteristics of peat deposits in these locations varies according to their mode of formation. Given the importance of material properties in governing landslide behaviour (Crozier, 1986; Selby, 1993), a brief discussion of the genesis of different peat deposits under varying climatic and topographic regimes is justified.

2.1.1 The formation and characteristics of peat

Peat accumulation has been studied in many contexts in recent years, and most thoroughly by Clymo (1978; 1984; Clymo *et al.*, 1998). Common to other accounts (Landva and Pheeney, 1980; Hobbs, 1986), his research considers peat as a two-part system, consisting of the acrotelm and the underlying catotelm. Avoiding potentially misleading references to characteristic vegetative components or layer depths (Bragg and Tallis, 2001), the two components can be simply defined as follows: the acrotelm is the thin aerobic surface layer of the mire, composed of predominantly living vegetation, and the catotelm is the thicker anaerobic zone below consisting of dead and decaying plant material. Peat accumulation rates are governed by the mean long term water table height, i.e. the depth of the acrotelm. When surface plant matter dies, it decays and plant mass is lost, as gas, by leaching or removal by small invertebrates. This occurs mainly under aerobic conditions, and consequently, the remaining non-decayed plant structures collapse, increasing the bulk density of the layer in which they reside. This permits capillary rise, raising the water table, and with it the permanently waterlogged and partly decayed catotelm upper boundary (Clymo, 1984). This is balanced to some extent by loss of matter in the catotelm, predominantly as methane gas. The interactions between the acrotelm and catotelm boundary, as mitigated by water table fluctuations, changes in chemical and physical states, and secondary rates of decay within the catotelm complicate the explanation further.

Definitions of peat as a soil or land-cover unit usually relate to the conditions under which it is formed. Most peat is found in bogs, leading to its description as either 'blanket bog' or 'raised bog' and collectively as ombrogenous mire (Tallis *et al.*, 1997; Bragg and Tallis, 2001) (Figure 2.1). The complexity of this terminology at even the broadest of scales has been noted by many authors (Taylor and Smith, 1980; Lowe and Walker, 1997). Simplifying the matter, Lowe and Walker (1997) describe *all* waterlogged areas that develop peat through reduced floral decay and under anaerobic conditions as mires (Moore, 1986). *Soligenous* mires form where high water tables induce peat formation through drainage impedence; *topogenous* mires maintain high water tables where peat develops over water trapped in an enclosed basin; and *ombrogenous* mires remain waterlogged through high atmospheric moisture conditions. Soligenous and topogenous mires form part of the hydroseral sequence, and if nutrient rich, with high organic productivity are eutrophic and known as fens. If low in organic productivity and nutrient poor, they are oligotrophic, and known as valley bogs. Most ombrogenous mires (or 'bogs') are oligotrophic, and fall into one of two categories, 'raised bog' or 'blanket bog' (Lowe and Walker, 1997). The former are predominantly discrete lowland domed features, while the latter form more continuous blankets at altitude (Barber, 1981). However, it has been observed by Lindsay *et al.* (1989; in Bragg and Tallis, 2001) that these probably represent endpoints in an ecological continuum that includes forms of 'intermediate bog.' This thesis is mainly concerned with the 'blanket bog' system of ombrogenous mires, as it is within these peatlands that most recorded peat mass movements occur. These mire types have the highest



Stage	Mire type	Nutrient source	Nutrient status	Common plant communities	pH of peat	Specific gravity	Organic content	Water content (%)	Liquid limit (%)	Permeability	Notes
					Decreasing as conditions become more ombrogenous		Increasing with height above the substrate			Permeability is higher in more fibrous less humified peats	
THIRD STAGE Above perimeter ground surface	Blanket bog	Rainfall only	Poor	Heather Purple moor grass Cotton sedge Deer sedge Sphagnum Cloudberry Ling	< 4	1.4	> 98%	2000 to 1000	1500 to 1000		Blanket bogs found at highest altitudes, over greatest range of relief, subject to intense orographic rainfall, liquid limit may readily exceed moisture content - majority of failures reported here
	Raised bog	Ombrogenous	Oligotrophic								
SECOND STAGE Above perimeter groundwater level Below perimeter ground surface	Raised bog	Mixed	Mixed	Willow Alder Sallow		1.4 to 1.6	> 80%	1000 to 500	900 to 600		Raised bogs occur at lower altitudes, relief largely a function of differential peat accumulation, few associated failures
	Fen carr	Rainfall and run-off	Mesotrophic	Fen mosses Spearwort Saw sedge Sedges Meadow rue							No failures reported in basin bogs
	Fen	Groundwater run-off and rainfall	Rich Eutrophic Minerotrophic	Fen mosses Spearwort Saw sedge Sedges Meadow rue	< 5	1.6		500 to 200	600 to 200		
FIRST STAGE Below ground water level	Swamp	Flowing water run-off and rainfall	Minerotrophic	Water lily Submerged plants							
	Lake	Rheotropic				1.6	< 10%	< 200	< 200		

Figure 2.1. Mire stages, morphology, flora and associated physical and chemical properties of peat (after Hobbs, 1986). Peat failures are generally only associated with blanket bog or raised bog.

moisture contents, the lowest permeabilities and occur over the steepest ranges of relief of all the mire types (Figure 2.1). All of these factors favour a disposition towards instability.

The physical characteristics of materials to a large extent determine their behaviour, particularly with regard to susceptibility to erosion processes. Peat is no different in this respect, yet as material, it is relatively poorly understood. Peat deposits are not composed of mineral particles, rather vegetative matter in various states of decomposition. In the engineering terminology, from which most physically based classification of material originates, peat is described as comprising two materials: fibres and filling (Silfverberg, 1955; Sellmeijer, 1994). The filling or soil matrix is regarded by many as clay-like (Landva and Pheeney, 1980; Hobbs, 1986), while the fibres are regarded as more vegetative structural components than a part of the peat 'soil' (Boelter, 1968; Fox and Edil, 1994). The relative importance of the fibres and matrix is dependent upon the degree of decomposition (or humification) of the vegetation. These properties of peat require a different form of description to that of gravels, sands and clays. The dichotomy between peat and other soils is highlighted in examining the Unified Soil Classification System (USCS) and the British Soil Classification System, both of which have been designed for the assessment of soil engineering characteristics. Quantified physical parameters such as fines (particle) content and consistency limits are used to define boundaries between soil groups. Although these can satisfactorily be determined for mineral soils, they either do not apply (mineral fines content) or are difficult to apply (consistency limits) in organic soils, and as a result, peat is excluded in definition, other than as a catch-all term for all highly organic soils.

The soil mechanics of minerogenic materials considers the interaction of particles at point contacts and the response of water held in pores to applied loads. The situation with peat is complicated by its unique micro- and macro-structures. Plant fibres and their cellular structures are the mineral grain equivalents in peat, and while water is held between these in the 'pores' of the peat matrix, water is also held *within* the plant cells themselves. Hence, where clay may have two types of bound water - pore water and adsorbed water, peat has a third additional supply: cell water. Furthermore, depending on the state of decomposition of the constituent fibres, they will act to provide an additional 'cohesion' (in the form of tensile strength), resulting in an anisotropic rather than isotropic shear strength. Where mineral particles are found in conjunction with the peat (in transition peats, inwash layers, and immediately overlying clay substrates), the situation is complicated further. It becomes clear that peat must be examined in terms of its fibre structure, as well as in general terms used for other soil types.

The special water relationships that characterise peat also merit further discussion. The physical properties and engineering characteristics of peat are profoundly influenced by its water content. Hobbs (1986, p27) states that *'...undoubtedly the most striking characteristic of peat is its ability to hold water...'*. Despite its exceptionally high moisture contents, its shear strength may be significantly greater than would be expected, although this is contingent upon the reinforcing effects of fibres, such that *'...in the virgin [unloaded] state...the relationship between water content and strength is frequently perverse...'* (Hobbs, 1986; p27). Furthermore, water content, and the physical properties dependent upon it, may be spatially very variable. Peat properties dependent on water content include wet bulk density, degree of saturation, consistency limits, shrinkage and shear strength.

The permeability of peat, i.e. its ability to allow the passage of water through its structure, is of particular relevance in slope stability studies. In a permeable layer, movement of water through the soil matrix may occur under seepage. When this seepage acts horizontally, it imparts a frictional drag in the direction of movement on the particles between which it flows. This seepage force counteracts gravitational forces on the plane of movement and reduces the effective normal stresses on that plane. Where seepage is large enough (either horizontally or vertically), gravitational forces may be completely negated, and the material exists in a state of zero strength. Any disturbance to this state results in failure. Conversely, where a soil has minimal permeability, pore water cannot escape under the application of an applied force, and there is a consequent increase in pore water pressure. This also acts to counter gravitational forces and reduce the strength of the material.

Although there are differences dependent upon genesis between bog and fen peats, at a gross scale Maltby and Proctor (1996) note that there is a great deal of overlap in physical properties between peat formed in differing settings (Figure 2.1). Broadly speaking, fen peats have higher dry bulk densities (averaging around 0.3 Mg m^{-3}), higher cation concentrations, higher ash contents and more neutral pH than bog peat (bulk densities around 0.1 - 0.2 Mg m^{-3}). Fen peats are also more diverse in type, as determined by the variety of depositional environments in which they are formed. Blanket bogs exhibit the lowest pH's, lowest specific gravity, highest organic matter contents, water contents and liquid limits. The range of properties from fen peats through valley basin deposits and on to blanket bog is considerable.

2.1.2 The spatial distribution of peat deposits and peat mass movements

Peat in its many forms covers over 3% of the Earth's land surface. A majority of this is found in Russia and Canada, but significant amounts mantle the landscapes of the United States, Indonesia and Finland. Landslides have yet to be recorded in these major areas of deposit (Table 2.1). The most recent global survey of peatland resources (Lappalainen, 1996) revealed that the status of peatlands in many countries is poorly understood, particularly those containing the largest deposits. The most thorough surveys (e.g. UK) consider percentage peat cover by type (fen, bog, wetland), approximate age of peat initiation and system state, e.g. erosive phase (Burton, 1996). The more superficial studies (e.g. Canada or Australia), assess little more than overall kilometre coverage (Rubec, 1996; Lappalainen, 1996). A cursory examination of peatland literature reveals wide-ranging discrepancies in minimum depth and percentage of organic matter required to regard a 'soil' as peat, despite many years of discussion (e.g. Proceedings of the International Peat Society, 1968, 1972, 1980). Both genetic and structural approaches have been considered. The all encompassing categorisation of peatlands as 'mires' still persists in the consideration of the global distribution of peat deposits. For the purposes of this review, peat deposits are referred to as organic soils that have been quoted as at least 0.3 m in depth (excluding the depth of living surface vegetation structures), and comprising over 60% organic matter (Akroyd, 1964).

Table 2.1. The global distribution of peat deposits and the number of peat mass movements (based upon Lappalainen, 1996).

Country	Number of reported peat failures	Total peat area (km^2)	% land area with peat cover
Argentina	2	500	2.60
Australia	> 20	15000	0.002
Canada	1	1113270	12
England	26	3986	3.1
Falkland Islands	3	290	> 45
Germany	> 2	5850	4
Ireland	36	11757	17.2
Malaysia	1	25364	7.7
Northern Ireland	28	1713	12.4
Scotland	30	11948	15.5
Wales	2	1588	7.6

Table 2.1 shows the distribution of peat deposits and the location of reported mass movements across the globe. Apart from the British Isles, reports of peat mass

movements relative to the abundance of peat resources seem scarce. Beginning in Europe, *moorbruchkatastrophie* (literally, 'catastrophic moorland break') have been reported in Germany by among others Vidal (1966) and Klinge (1892), where mires cover some or 14 000 km^2 or 4% of the land surface (Steffens, 1996). In the scattered raised and transitional bogs of Switzerland, one large *glissement en tourbiere* (literally, 'slip in peat') has been recorded (Feldmeyer-Christe, 1995). Outside Europe, a significant number of examples can be found within Australasia. Oakes (1999) noted a failure in the heavily agricultural wetlands around Sydney in Australia (Lappalainen, 1996). Campbell (1981) described tens of peat debris-slides on the peaty soils slopes of Campbell Island, off the coast of New Zealand. Selkirk (1996) examined several peat slides on Sub-Antarctic Macquarie Island, where peat cover is extensive on coastal hills. Wilford (1966) described a bog burst in Malaysia, where most of the 25 000 km^2 (7.7% of the land surface) of peat can be found in water-saturated basins in the coastal lowlands (Ambak and Ah Chye, 1996). Wilson *et al.* (1993) highlight the discovery of several peat slides by other authors (Cawkell,1960; Strange, 1983) on the Falkland Islands, where peat accounts for 45% of the land surface. The remaining examples have been reported as peaty-soil slides in Argentina's Fuegia bogs which total some 500 km^2, or less than 2.6% of the land area (Rabassa *et al.*, 1996); and in Canada, where one artificially triggered slide was reported by Hungr and Evans (1985). Two key points may be drawn from this brief survey. Firstly that the number of failures relative to the areas of peatland involved seem very low, and secondly that the peat environments in which they occur are diverse in their topographic setting (coastal lowland to upland) and mode of formation (infilling basins to precipitation-fed upland bogs). The potential difficulty in relating failures to material type on a global scale is clear.

This sparse distribution of events relative to areal coverage of peat is not reflected in the UK and Ireland, where a mixture of fens and bogs represent over 8% of the land surface (Taylor, 1983). In these relatively highly populated locations, the functioning of peat systems often has impacts upon the general population. For example, most major river systems in the UK emanate from blanket peat areas in the uplands of England, Scotland and Wales. Peat in these areas affects water quality, freshwater fish populations and reservoir siltation rates (Burt *et al.*, 1997). In Ireland, peat is a valuable economic resource, harvested as fuel and used in industry (Cruickshank and Tomlinson, 1990; Shier, 1996). Furthermore, mires across the UK and Ireland form part of the cultural landscape associated with the 'uplands', including farming practices and hunting of game birds. Hence, peat degradation in these areas in any form has increasingly become an issue in the natural sciences, conservation and in upland

Figure 2.2. Peat deposits (after Taylor, 1977) and distribution of peat mass-movements in England, Scotland and Wales.

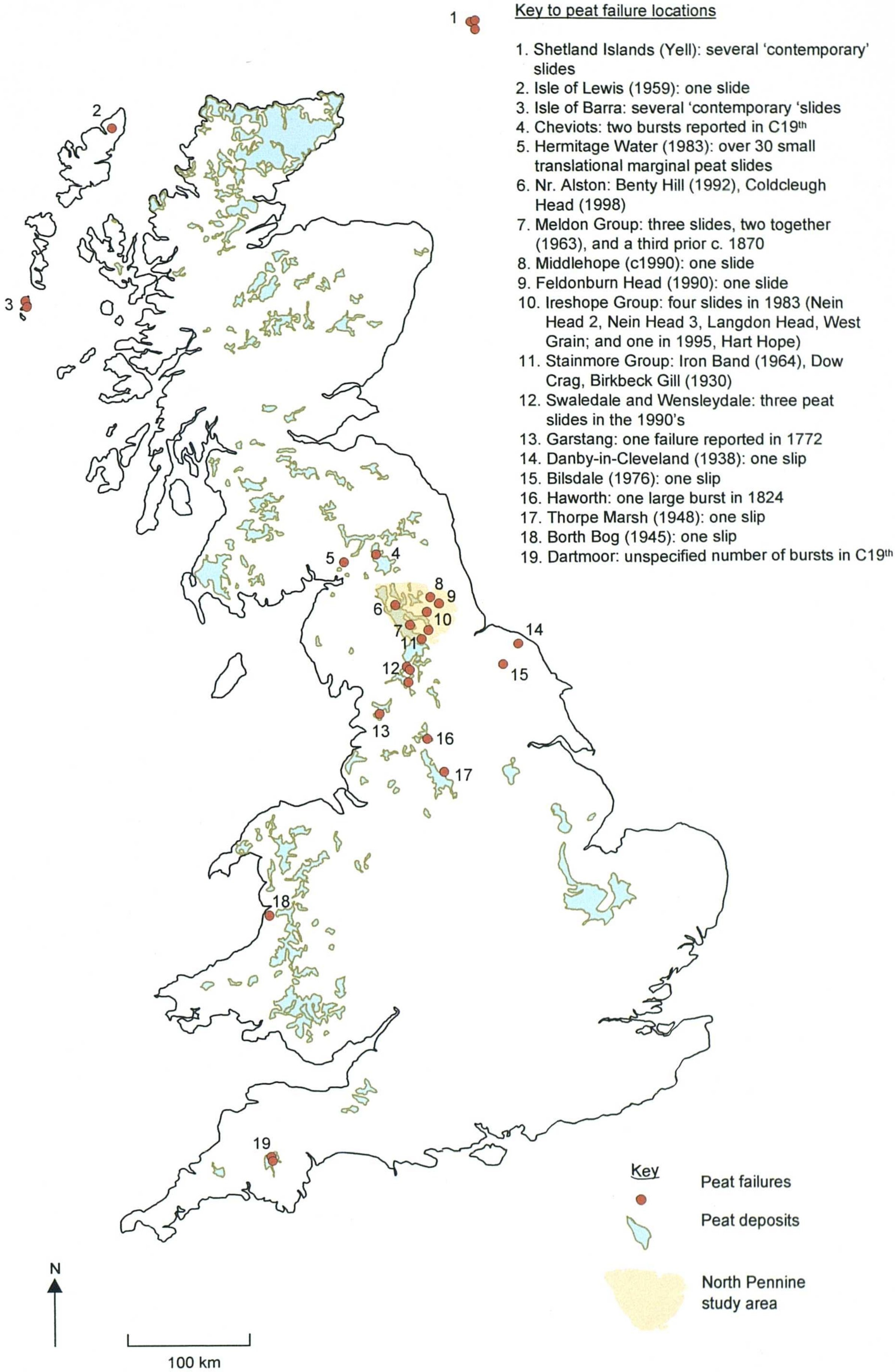
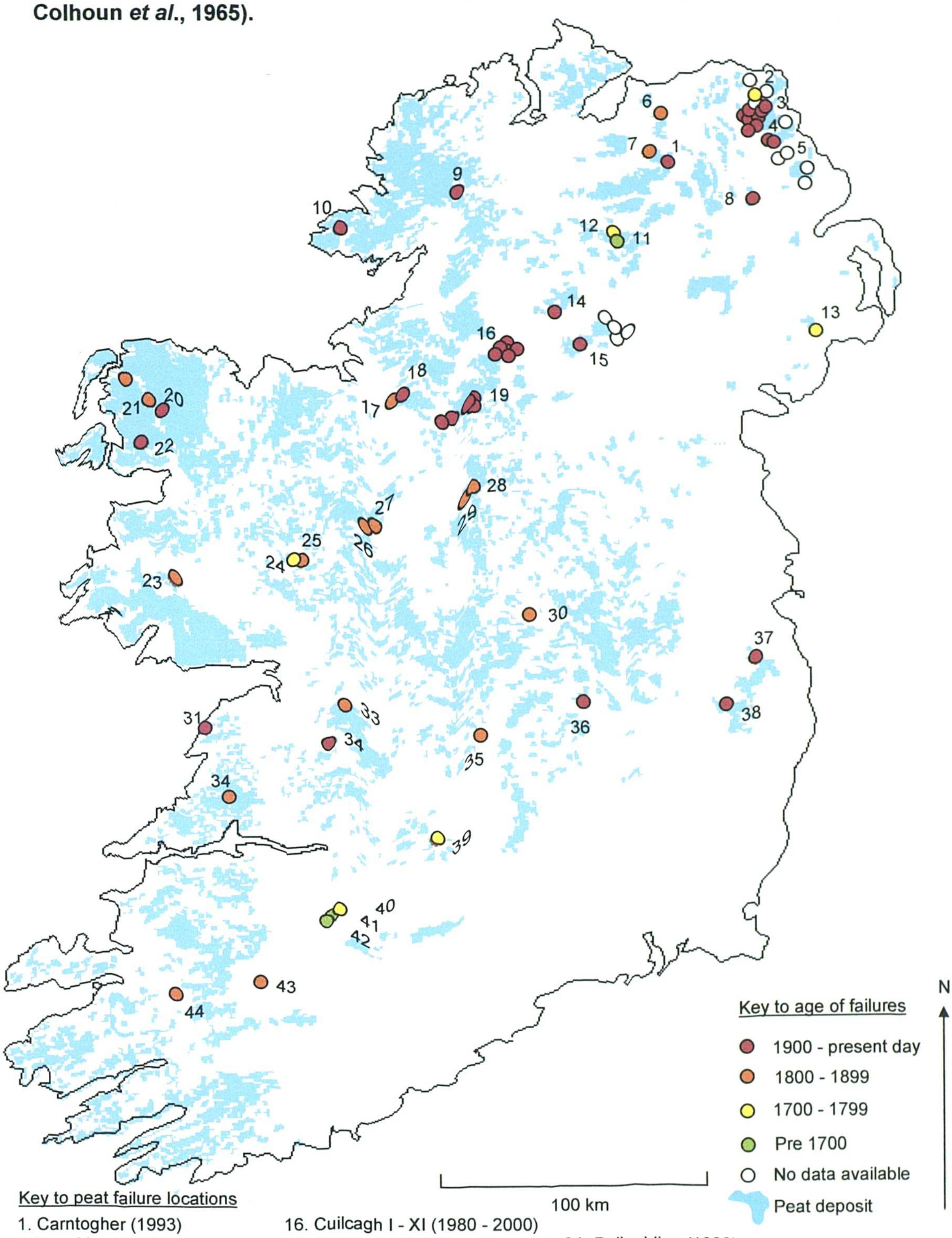


Figure 2.3. Peat deposits in Ireland and Northern Ireland (after Hammond, 1979) and peat mass movements in Ireland and Northern (after Cruickshank and Tomlinson, 1990; Colhoun *et al.*, 1965).



Key to peat failure locations

1. Carntogher (1993)
2. Knocklayd (1788)
3. Glendun (1963)
4. Slieve-an-Orra I - VII (1980)
5. Skerry Hill (1991)
6. Ballywindelland (1824)
7. Dungiven (1895)
8. Randalstown (1835)
9. Barnesmore (1963)
10. Meenacharvy (1945)
11. Clogher I (1640)
12. Clogher II (1712)
13. Monabogh (1780)
14. Slieve Rushen (1965)
15. Carrowmaculla (1979)
16. Cuilcagh I - XI (1980 - 2000)
17. Geevagh I (1832)
18. Geevagh II (1984)
19. Slievenakilla I - III (1986)
20. Bellacorrick (1988)
21. Owenmore (1819)
22. Glencullin (1931)
23. Joyce Country (1821)
24. Dunmore I (1745)
25. Dunmore II (1873)
26. Castlereagh I (1870)
27. Castlereagh II (1833)
28. Camlin Valley (1809)
29. Newtonforbes (1883)
30. Clara (1821)
31. Ballaghline (1900)
32. Kilmaleady (1821)
33. Loughatorick (1890)
34. Killanena (1934)
35. Clonagill (1871)
36. County Offaly (1906)
37. Powerscourt (1938)
38. Moanbane (1937)
39. Dundrum (1788)
40. Castlegarde (1708)
41. Charleville I (1708)
42. Charleville II (1697)
43. Farrendoyle (1840)
44. Knocknageeha (1896)

management.

Britain's relatively high latitude (50 to 60°) and island status produce a cool-temperate maritime climate conducive to peat formation (Taylor, 1983). High humidities, low evaporation and intermediate temperatures aid peat accumulation at low altitudes while a nearly sub-arctic upland climate and steep climatic lapse rates promote it at high altitude (Taylor and Smith, 1980). Peat growth is further aided by a topographic bias towards extensive upland plateau at higher altitude, as controlled by geological structure and geomorphological history. Hence, it is unsurprising that peat deposits are distributed mainly in the north and west, and only sporadically in the south and east. In the latter regions, Taylor (1983) notes an evaporation excess for much of the year, and the excess moisture conditions required for growth result mainly from impeded drainage in the coastal lowlands.

Figures 2.2 and 2.3 illustrate the distribution of peat deposits in Britain and Ireland. Pearsall (1950), Taylor (1983) and most recently Burton (1996) have undertaken nation-wide assessments of moorland and peat resource. Burton summarises the nature and distribution of much of the British fens and bogs, and this survey provides a good basis from which to describe British peat mass movements. Employing the criteria for Scottish peats of 60% organic matter of greater than 50 cm thickness (Burton, 1996), peat deposits are very widespread. Basin and valley peats together cover approximately 666 km^2 (<1% land surface), though there are no reported failures within these types of mire. There have, however, been a number of failures within the deep blanket peats that occupy 6994 km^2 (9%) of Scotland. In west Scotland and the Outer Hebrides, mantled by blanket peat from sea-level to 350 m in altitude, a number of failures have been noted in peat that averages 2 m in depth. The most famous occurred in Solway Moss in 1771, described by Walker (1772) and recounted by a number of authors since (Lamb, 1982; McEwen and Withers, 1989). More recently, Ashmore *et al.* (2000) have highlighted contemporary and potentially ancient peat slides in the Borve Valley, Barra, in the Outer Hebrides. Bowes (1960) noted a bog burst on the Isle of Lewis that occurred in 1959. Further north in the Shetland Islands, where blanket peat accounts for a third of the land area, Veyret and Coque-Delhuille (1993) report several peat slides of recent age on Yell. The thinner but widespread blanket peats of southern and central Scotland are home to a cluster of shallow failures, described by Werrity and Ingram (1985) and Acreman (1991). These peaty-soil slides occur at the blanket margins, where peat becomes transitional as it grades into mineral soils. To date, no failures have been reported in the extensive blanket peat deposits of the north-east Grampians and Monadhliath mountains, where peat reaches up to 3 m in depth, half of which is actively eroding.

In England, examples of peat failures are more numerous, extending from the border as far south as Dartmoor. Here, peat is so defined where it exceeds 40 cm in depth, though Burton (1996) fails to define a percentage of organic matter. The northernmost example is found in the Cheviot Hills near the English/Scottish border, where Muschamp-Perry (1897) and Clough (1888) describe 19th century examples. The North Pennines, described by Johnson and Dunham (1963), Bower (1959) and Warburton (1998) provide the most intense regional clustering of peat slides in the UK. Over 14 examples exist in blanket peat ranging in thickness and nature (Crisp *et al.*, 1964; Carling, 1985, 1986; Johnson, 1992; Warburton *et al.* in press). This area is described in greater detail in section 2.5.2, as it forms the main research region of this study.

Moving south, the extensive research into peatland processes of Bower (1959, 1960, 1961, 1962) and Tallis (1964, 1973, 1985, 1987) fail to establish any further examples in the mid and South Pennines. However, Mills *et al.* (in preparation) describe recent peat slides in Swaledale and Mallerstang. To the east, in blanket bog of the North Yorkshire Moors, Hemingway and Sledge (1941-46) highlight a burst dating from 1938 and Beven *et al.* (1978) a small peat slip in transitional peat material in Bilsdale. Evans (1993) notes two adjacent bog bursts in Lancashire of differing, but recent age. Pennant (1722) has logged the occurrence of a large failure in the raised bogs of Garstang (Burton, 1996), the date of which is unknown. Bronte (1824) narrates the occurrence of a large burst in Haworth. Nearby, another historically famous burst has been described in the valley bog of Chat Moss (Crofton, 1802; Taylor, 1983) which probably peaked at around 10 m in depth at the time of failure. The remaining examples from the less prominent peatlands in the southern half of England and Wales are not so well documented. Ward (1948) has noted the geotechnical failure of a raised bog margin along the coast of Wales. Despite the presence of significant hill and blanket peat deposits approaching 1558 km^2 (7.6%) in extent, no other failures have been reported in Welsh uplands. Finally, Vancouver (1808) comments upon historical bog bursts of unspecified age in the blanket bogs of Dartmoor.

Over 50 examples of peat mass movements have been recorded in Northern Ireland and the Republic. Figure 2.3 illustrates their widespread and even distribution across both regions. The range of peat types in Northern Ireland has been well documented by Cruickshank and Tomlinson (1990), but the Republic is less well studied. In the former, there is very noticeable clustering on the Antrim Plateau in blanket peat above 330 m (Cruickshank and Tomlinson, 1990), with bursts described by Colhoun *et al.*

(1965) and slides by Tomlinson and Gardiner (1982) and Wilson and Hegarty (1993). Few other examples have been reported for the remaining of Northern Ireland's 1400 km^2 (2.5% land area) of blanket bog. In the less widespread lowland raised bogs (252 km^2; Shier, 1996), which are almost entirely managed in some shape or form, two sets of bog bursts in Randalstown and Clogher have been noted (Perry, 1981). In the Republic of Ireland, mass movements are more widespread, though most examples have been reported in the blanket bogs of the west (Donegal, Sligo, Clare and Kerry: Praeger, 1897; Cole, 1897; Bishopp and Mitchell, 1946; Alexander *et al.*, 1986; Wilson *et al.*, 1996), and in the more central and eastern mountainous blanket bogs (Fermanagh, Leitrim, Cavan and Wicklow: Mitchell, 1935; 1938; Delap and Mitchell, 1939; Tomlinson, 1981; Large, 1991). Again blanket bog is more widespread (7700 km^2; 11.5% land area) than raised bog (3000 km^2; 4.3% land area), with just over 50% of the peat deposits managed to some extent (Shier, 1996). Only isolated reports of failures in raised bog exist (e.g. Charleville, 1607, cited in Sollas *et al.*, 1897), and for both Ireland and Northern Ireland, reports of peat mass movement events extend as far back as the 17th century (Feehan and O'Donovan, 1996).

This latter review of the UK and Ireland illustrates that peat mass movements occur across a range of peat forming environments, at altitude in blanket bogs and in the raised bogs occurring over lower relief. The potential for variability in physical properties and controls on instability across these settings is considerable. Despite the occurrence of failures in most peatland settings, peat landslides have rarely been reported outside the UK. The lack of sightings in the peatlands of greatest spatial extent (e.g. those of Canada or the United States of America) may reflect sparsity of human populations in these areas, rather than a reflection of peat characteristics. The next section highlights research (based mostly within the British Isles) on peat erosion, and illustrates the significance of peat mass movements within this context.

2.2 The erosion of blanket peat: mass movement morphology in context

Despite the extensive global distribution of peatlands, research into natural forms of degradation has been limited mainly to the UK and Ireland. Detailed studies of large-scale blanket peat degradation began in earnest in the late 1950's with Bower's (1959) extensive study of the *distribution* of blanket peat erosion through the full extent of the Pennine chain. Mapping of erosion patterns from aerial photographs corroborated by ground surveys led Bower to establish a classification system for peat erosion that has been a benchmark since. On the basis of blanket morphology and erosion patterns, Bower (1959; 1960) suggested there were two main types of erosion, i) erosion by water (fluvial) and ii) erosion by mass movement. In the case of the former, erosion of the blanket peat could proceed in three ways depending on relief, peat depth and climate. Regarding dissection as the primary process (in part due to consistency of mapping), Bower distinguished two different indicative patterns:

Type 1 dissection: similar in pattern to anastomosing channels (Cruickshank and Tomlinson, 1990), except with alluvium or bedrock replaced with peat 'islands' and occurring on shallow slopes less than 5 degrees with peat depths in excess of 1.5 m.

Type 2 dissection: linear patterned gullies found on steeper slopes in excess of 5 degrees, and usually on peat depths less than 1.5 m.

Bower suggested that a third mechanism involved sheet erosion, rainsplash and wind acting in combination on exposed summits, and in the reworking of exposed gully faces of Type 1 and Type 2 dissected areas. Erosion by mass movement, noted as common on the steeper slopes in the Southern Pennines, was not substantiated within Bower's work, though it was cited as potentially significant at blanket margins (tears/slides) and as isolated inner blanket occurrences (bursts).

The *causes* of peat erosion were addressed in two subsequent papers by Bower (1961, 1962), in which the onset of erosion was considered as an endpoint to accumulation (after Conway, 1954), a concomitant to accumulation (after Lewis, 1904; and Pearsall, 1950), a response to climatic change (after Geikie, 1866; and Crampton, 1911), or caused by increased biotic pressure (after Fraser, 1933; and Fenton, 1951). Conway's theory suggested that as an accumulating deposit, blanket peat could not deepen indefinitely, and hence erosion represented a natural endpoint to the evolution of upland peat environments. Lewis (1904), and then Pearsall (1950) suggested peat erosion might be cyclic within longer term periods of accumulation. Climate change was implicated in both of the previous theories, but also cited as a separate control by Geikie (1866), Lewis (1904) and then Crampton (1911). It was suggested that less moist climatic regimes might be responsible for both cessation of peat accumulation and depletion of surface protecting plant species, allowing erosion to exploit surface dessication cracks. Similar changes in vegetation cover and surface structural damage were associated with biotic causes of erosion (Fraser, 1933; Fenton, 1951). Initially, Radley (1962) took issue with Bower's classification and interpretation, attributing peat erosion almost entirely to the extension of summit drainage systems initiated by human disturbance of vegetation cover. This largely anthropogenic theory of erosion development incorporating grazing, firing, cutting and draining as causes practically excluded the possibility of widespread erosion pre-human interference, and was poorly substantiated with evidence. Nevertheless, Tallis (1965, 1973) extended some of the ideas of Radley in research on the South Pennines, attributing gully systems to the encroachment of pre-glacial drainage lines into the blanket margins, and associating his extending summit gully systems to dieback of vegetation related to grazing and air pollution. Later (1985, 1987), Tallis returned to Bower's scheme, following the approaches taken by others in attempting to apply Bower's classification to specific regions of the Pennines (Tallis, 1964, 1965; Mosley, 1972; Mayfield and Pearson, 1972), and elsewhere (Slater *et al.*, 1980; Tomlinson, 1981). Subsequent studies continued in the same vein (Bradshaw and McGee, 1988; Cruickshank and Tomlinson, 1990; Warburton and Wishart, 2002). In most of these cases, the two-part gully based classification is accepted, but with some reservations based on local or regional controls such as climate, relief or peat depth. Tallis (1985) produced a fourfold framework encompassing the variety of theories for peat erosion, known as the fluvial (stream extension), biotic (burning, grazing and pollution), karstic (subterranean drainage) and catastrophic (bog-bursting and sliding) theories.

Investigation into processes of peat erosion outside the established frameworks of Bower and Tallis has become increasingly prevalent. Mass failures in coastal peat deposits have been recorded as flake failures by Allen (1999), and fluvial erosion and transport of peat blocks have been reported by Evans and Warburton (2001). The significance of subterranean drainage in the form of pipe erosion has been investigated primarily by Gilman and Newson (1980), and later, Holden and Burt (in press). Increasingly, the mass movement component of peat erosion has also been recognised (Carling, 1986; Large, 1991; Dykes and Kirk, 2001), though few researchers other than Bower (1962), Tallis (1985) and Evans and Warburton (2001) have actively attempted to assess its significance. The latter have considered quantitative aspects of peat erosion within the context of wider upland geomorphological process frameworks. The relative position of peat mass movements within the earlier framework of Tallis (1985) and this more recent example are shown in Table 2.2. There are five major causative factors in peat erosion. Surface erosion by water (fluvial), erosion as a consequence of biotic activity (biotic), subsurface erosion by water (karstic), erosion by catastrophic mass movement (catastrophic), and erosion by wind (aeolian).

While many attempts at explaining bog burst and peat slide occurrence had been made prior to the 1950's, it was only with the work of Pearsall, Conway, Bower and Tallis that

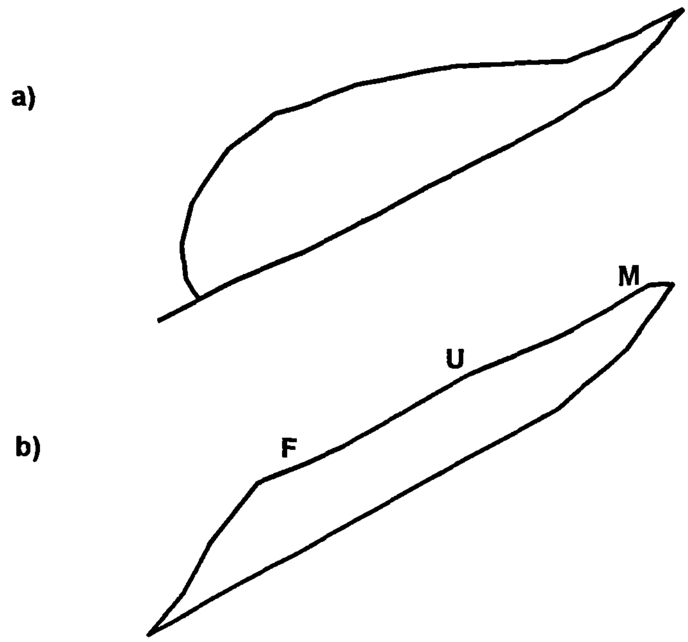


Figure 2.4. Whole blanket response to mass-controlled internal defomation (Pearsall, 1950)

Erosion Type	Causative Process	Visible Form	Examples
Fluvial	Incision by water action	Gullies	Bower (1961), Newson (1976), Radley (1962)
	Cycles of wetting/drying	Dessication cracks	Barnes (1962), Davies (1945), Pearsall (1950)
	Headcut erosion by water action	Peat blocks	Evans and Warburton (2001)
	Artificial provision of drainage	Gripping	Bower (1961, 1962), Moore (1968)
Biotic	Pollution induced loss of Sphagnum cover	Bare patches of eroding peat	Conway (1954), Tallis (1964), Bower (1962)
	Grazing induced loss of vegetation cover	Bare patches of eroding peat	Conway (1954), Mayfield and Pearson (1972), Radley (1962), Moore (1968)
	Burning/harvesting loss of vegetation cover	Bare and mechanically altered patches of eroding peat	Cruickshank and Tomlinson (1990), Moore and Bellamy (1974), Taylor and Tucker (1968), Bower (1961)
	Trampling by sheep/slow mass movement	Sheep scars/arcuate tears	Bower (1961)
Karstic	Tunnelling by water action	Pipes	Taylor and Tucker (1970), Newson (1976), Holden (2001)
Catastrophic	Rapid mass movement	Slide and burst scars	Pearsall (1960), Tallis (1985), Bower (1961), Mayfield and Pearson (1973), Warburton *et al.* (in press)
Aeolian	Wind erosion	Bare patches of eroding peat	Warburton (in press)

Table 2.2. Peat erosion systems and their causes (partly modified from Slater *et al.*, 1980; Evans and Warburton, 2001)

an integrated approach to the catastrophic mechanism of peat mass movements began to develop. Initially bog bursts were seen as release mechanisms for peat masses destabilised by the attainment of a critical peat depth. Pearsall (1950) described bog peat as analogous to a 'drop of viscous fluid'. Such peat would either flow or develop its own drainage system (Figure 2.4). Rather than a fluid drop bounded by a surface skin of vegetation (Figure 2.4a), bog morphology in profile could be represented by the schematic in Figure 2.4b. Drying would lead to shrinking of the peat mass, and stretching and tearing of the surface skin between U and M, under the downslope driving mass of the peat body. The lower, more saturated section of bog, between F and U would not be prone to these processes, but become deeper and heavier until unstable, subsequently developing an erosion system. Peat failures were considered as a catastrophic release of this part of the peat mass. Conway (1954), following Pearsall (1950) saw bog bursts as blanket peripheral release mechanisms responding to the destabilising influence of rapid *Sphagnum* peat growth in central blanket areas. Johnson (1957) put this idea into a temporal framework, suggesting that such critical peat depths were attained during a 'post-mature' phase of bog development. Newbould (1958), with little substantiation, suggested a critical depth for bursting of 1.8 m. This phase and associated erosion (whether catastrophic or otherwise) was regarded as an inevitable consequence of continuing bog growth (Tallis, 1985). Bower (1959, 1962) pushed these ideas further, linking Pearsall's (1956) parallel rows of pools and furrows to slow, creep-induced tears. Bower suggests that these might be preparatory conditions for catastrophic failure, or a means by which the peat mass can adjust to build up of tension. Similarly, Bradshaw and McGee (1987) regard 'mass-flows' as an intrinsic peatland property, but fail to support this idea with field evidence. Tallis (1985) attempts to support the idea of a 'post-mature' stage. He has identified two distinct phases of erosion in southern Pennine peat using pollen stratigraphic records, both of which he associates with dissection and mass movement. Prior to each phase of erosion, the southern Pennine peatlands in question exhibited plentiful Sphagnum cover, much as the North Pennines now. Under the assumption that Sphagnum decline leads to peat degradation, Tallis suggests that the younger areas of North Pennine peat (3800 years old; Warburton, 1998) are currently in a state similar to that experienced by older peats in the South Pennines (5000 years old; Tallis, 1964) prior to their erosion. Within the peat stratigraphy, this change of regime is indicated by a shift from *Sphagnum* to *Eriophorum* spp in the pollen record. Using age as a basis for defining the erosive stage of a region may be erroneous, given the spatially widespread variability in the onset of peat accumulation. For example, Charman (2002), following Chambers' studies of Welsh peats (1981, 1982) illustrates a range in the time of onset of peat growth in the South Pennines equivalent to 5000 years.

Many of the aforementioned authors also attempt to relate mass movements to gully formation. Bower (1959) proposes that bursts and tears might act as drainage outlets from which dissecting systems develop. Gilman and Newson (1980) support the idea of bog bursts and peat slides being located along lines of preferential water flow not yet manifest as surface channels. Tomlinson and Gardiner (1982) and Tallis (1985) concur, suggesting that excess water build-up in accumulating bog masses would be expelled at 'exit points', either through the initiation of gullying or as mass movements. This led Tallis (1985) to reclassify erosion types as stream erosion (incorporating a Type 3 gully initiated by bog bursts), summit erosion and marginal recession. Bower's (1959) suggestion that the absence of scars may be indicative of their effacement by dissection systems certainly corroborates the general absence of extensive gullying in peat masses drained by peat failure scars.

Discussion thus far has centred on peat instability as a release mechanism for excess peat accumulation or water build up. Little attention has been afforded to peat failures as products of external driving forces for change, for example long term changes in climate, or isolated high magnitude climatic events. This reflects the fact that most accounts of climate-driven degradation focus on gully systems and changes in vegetation dieback. In the case of high magnitude low frequency events such as peat mass movements, short-term climatic triggers are more likely to be important, such as intense rainfall or snowmelt. Such events are usually noted on a case-by-case basis in association with specific peat failures rather than in the wider peat erosion literature. This will be examined further in the following chapter when bog bursts and peat slides are compared to long and short-term climate records. The next two sections describe the morphologies typical of peat slides and bog bursts, after which their position amongst other landslide types is considered.

2.2.1 Peat slides: morphology and definition

Peat slides are usually described as slab-like shallow translational failures, with a shear failure mechanism operating at the peat-substrate interface or below (Warburton *et al.*, in press). Subsequent to break-up of the blanket surface, large rafts and smaller blocks are transported downslope, in the main by sliding. A well-lubricated blocky mass may be generated by rapid remoulding during transport, leading to description of the events as 'bog' or 'peat-flows' (Colhoun *et al.*, 1965, Alexander *et al.*, 1986). In some cases, the association of peat slides with extreme rainfall events has led to their description as 'cloudbursts' (Hudleston, 1930). The breakdown of large slab-like masses of surface material with movement downslope, initiating as a shear failure and degenerating into debris flows corresponds most closely with Corominas' (1996) definition of a debris slide.

Morphological field evidence to support peat slides as distinct in form from bog bursts is widespread. Unfortunately, unlike bog burst studies, geomorphological maps indicating the morphological components of peat slides are rare. The photographed examples shown in Figures 2.5a to d are taken from a range of UK and Irish sites, but can be considered representative of slide populations as a whole.

Scar types range from crescentic (Werrity and Ingram, 1985) to linear (Hudleston, 1930; Carling, 1986; Johnson, 1992) and may be almost entirely excavated (Crisp *et al.*, 1964) or still contain significant amounts of material (Large, 1991) (Figure 2.5d). The scar areas themselves almost always reveal the peat substrate over the majority of the surface, whether this be clay (Tomlinson and Gardiner, 1982), clastic layers (Scott, 1983; Selkirk, 1996) or some composite of the two (Campbell, 1981) such as glacial till. Striations and gouging over the substrate surface, created by the scouring action of debris embedded in the basal material have occasionally been reported (Delap and Mitchell, 1939; Carling, 1986; Dykes and Kirk, 2001). In rare cases, peat slide morphology is associated with failure planes within the peat mass. Wilson and Hegarty (1993) noted multiple failures on Skerry Hill (Northern Ireland) as peat slides, on the basis of a clearly visible, striated slip plane within the peat.

Dependent on the quantity of material exported from the site, and the extent of slope-channel coupling, slides exhibit distinct depositional morphologies (Figure 2.6). In the main, this is manifest by a long runout zone (Wilson and Hegarty, 1993; Carling 1986), blocky levees along the scar edge and transport path (Johnson, 1992; Warburton and Higgitt, 1998), and isolated and clustered rafts of stranded peat blanket (Archer, 1992; Carling, 1985, 1986; Selkirk, 1996). Frequently, these deposits are reported as surrounded by a slurried and disaggregated peat veneer (Hudleston, 1930). It is also common to find pooled areas within the more massive debris, where hydrological discontinuities prevent drainage of surface water (Wilson and Hegarty, 1993; Selkirk, 1996).

Features that may indicate stress fields (Warburton *et al.* in press) across peat slides have been described at many sites (Figure 2.7). In the main these represent zones of tension manifest by narrow and deep cracking (Crisp *et al.*, 1964; Coxon *et al.*, 1989; Johnson, 1992), or occasionally wider and shallower surface tearing. Features

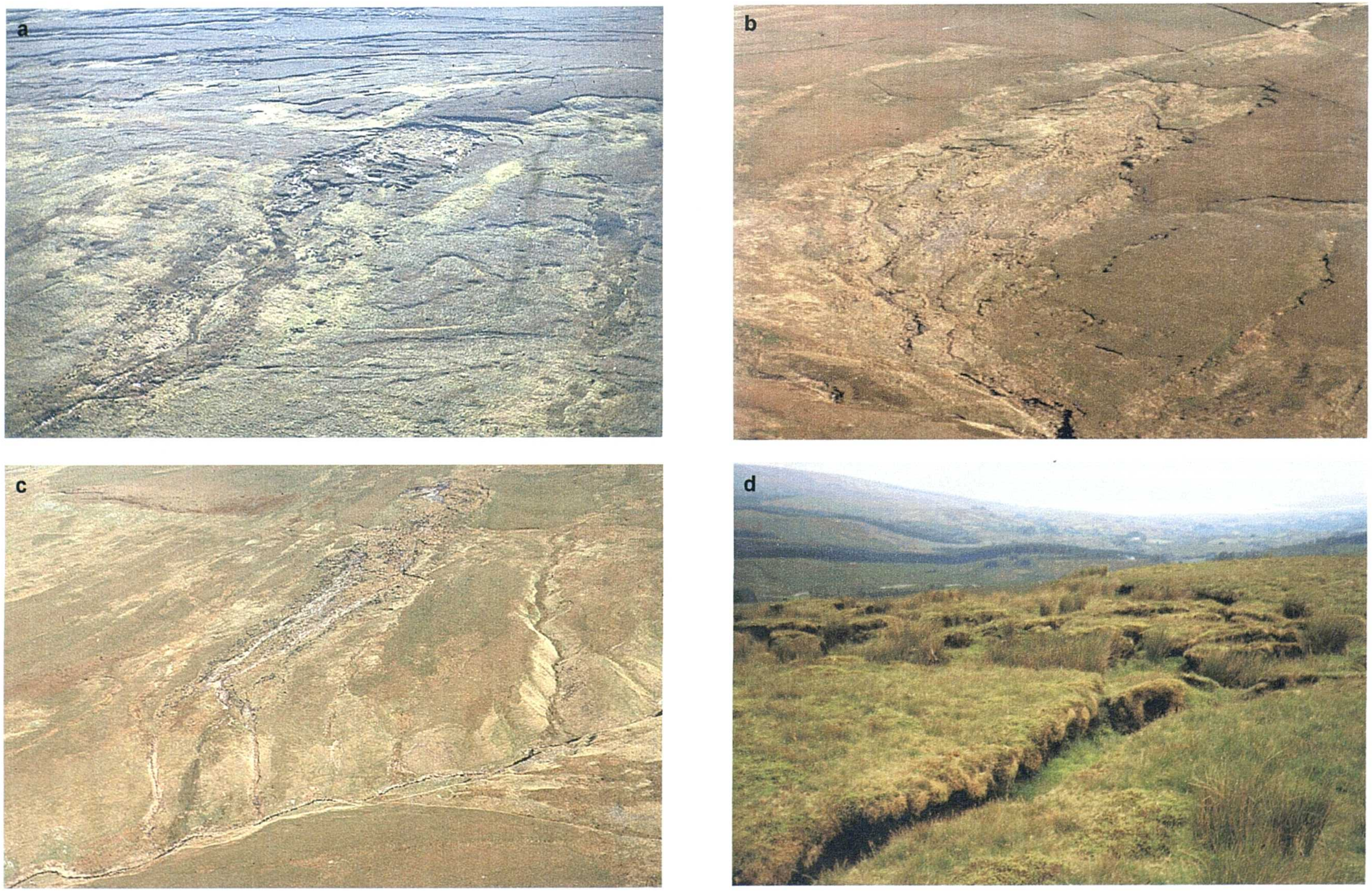


Figure 2.5. Examples of peat slides from the UK and Ireland, a) Nein Head 3 (1983), b) Langdon Head (1983), c) Hart Hope (1995), d) Slievenakilla (1986).

Figure 2.6. Peat slide depositional features: a) block beyond scar margin at Nein Head II (1983) peat slide, b) slurry over scar area at Nein Head II peat slide, c) rafting at Nein Head II peat slide, d) levee at Coldcleugh Head (1998) peat slide.

Figure 2.7. Peat slide extension features: a) block formation by cracking at Slievenakilla (Co. Leitrim), b) shallow surface cracking near scar margin at Feldon Burn (North Pennines), c) deep cracking within central rafts at Bloodybush Edge (Cheviots).

synonymous with zones of compression have also been recorded, in the main as upthrust margins (Johnson, 1992; Wilson and Hegarty, 1993) and compression ridges (Warburton and Higgitt, 1998).

Although less commonly reported than 'bog bursts', there are numerous reports of peat slides and yet virtually no attempt has been made to define peat slides as a distinct landslide type. Selkirk (1996) refers to Varnes' (1978) scheme, describing slides on Macquarie Island as events which '*...progress down and out on a more or less planar or gently undulatory surface with little rotational movement.*' Acreman (1991, p175) describes events in Scotland which:

> '...are distinct from bog bursts (e.g. Bowes, 1960), appear to be similar to those reported by Carling (1985) in the northern Pennines...while the initial failure probably involved sliding, subsequent liquefaction of the peat caused it to flow over the lower slopes...'

Few of the reported examples assess the nature of the failure mechanism or characterise the resultant morphology. More often than not, the terms 'burst', 'slide' and 'flow' are used interchangeably.

A number of features have been described as peat slides which have occurred in materials that on the basis of peat depth and organic matter content may be more truly described as peaty soils (e.g. Werrity and Ingram, 1985; Acreman, 1991; Gallart *et al.*, 1994). These are predominantly shallow translational landslides at the margins of blanket peat areas, or chute-like debris flows in steep slopes with minimal organic soil cover. Common characteristics include crescentic scar areas with long runout zones (Werrity and Ingram, 1985; Acreman, 1991; Gallart *et al.*, 1994), blocky deposits (Campbell, 1981), and rotational slides (or slumps) in which runout is minimal, and peat is not directly involved in failure initiation (Delap and Mitchell, 1939; Ward, 1948; 1955; Beven *et al.* 1978). In none of these cases are all morphological features traditionally associated with peat slides found together.

2.2.2 Bog bursts: morphology and definition

Bog bursts are described as particularly fluid failures, involving the rupture of the peat blanket surface or margin due to subsurface creep or swelling, with liquefied basal material expelled through surface tears, and the subsequent let down of the overlying peat mass (Hemingway and Sledge, 1941-46; Bowes, 1960; Warburton *et al.*, in press). They are characterised by amphitheatre shaped areas of disturbed (often sunken) blanket bog, arranged in concentric tears and rafts, with little substrate revealed, and without necessarily a clear scar face. The morphological description of a bog burst in Danby (Hemingway and Sledge, 1941-46, p281) embodies many of the features described for bursts elsewhere. The burst is described as follows:

> '...cracked and fissured, but is not broken into separate blocks...[its] broken surface averaged 5 feet lower than that of the undisturbed peat...the structure produced is one of collapse, consequent upon the removal of the peat from the lower layers of the bog...'

This is corroborated by Tomlinson (1981, p315), who notes for a burst in Fermanagh that:

> '...upslope of the narrower track is a wider, though shallower, amphitheatre...only arcuate islands of upper peat remain...long narrow 'crevasses' can be observed...extending from the edge of the burst into the surrounding blanket peat...'

The morphology associated with potential collapse of sub-surface peat structure most closely parallels Buma and Van Asch's (1996, p137) definition of a soil (debris) spreading failure, namely '*...the collapse of a sensitive soil layer at a certain depth, followed by either settlement of the overlying more resistant soil layer(s), or progressive failure throughout the whole sliding mass...*' Unfortunately, their review considers only mineral soils experiencing such morphologies.

There are many accounts describing the characteristic morphological components of bog bursts. The main 'scar' area can be defined as a 'subsidence' zone. Here, the peat surface is let-down relative to the surrounding blanket, with export of the subsided material varying from site to site (Tomlinson, 1981; Alexander *et al.*, 1986; Wilson *et al.*, 1996). In the least disturbed examples, the peat surface can be seen to break up in a pattern of concentric peat masses (Figure 2.8), separated by wide and often deep fissures or tears (Latimer, 1897; Mitchell, 1935; Alexander *et al.*, 1986). Frequently, substrate may not be exposed at all (Mitchell, 1935, 1938; Colhoun *et al.*, 1965; Tomlinson, 1981). Hence, unlike peat slides, the boundary between disturbed and undisturbed material is often indistinct. In the case of the former, a clear scar edge is exhibited, while in the latter the blanket is only undisturbed beyond the outermost extent of tearing. In many cases, this may incorporate large areas of peat mass that has barely if at all, been transported. For example, with reference to an amphitheatre-shaped 'source area', Colhoun *et al.* (1965, p167) note that '*...the point at which the bog flow began could not be determined exactly.*' In the most disturbed cases, where transport dominates over subsidence, bog bursts may develop scars similar to those of peat slides, where all but a few concentric rafts remain within the original amphitheatre-a

Vertical exaggeration (2x)

b

c

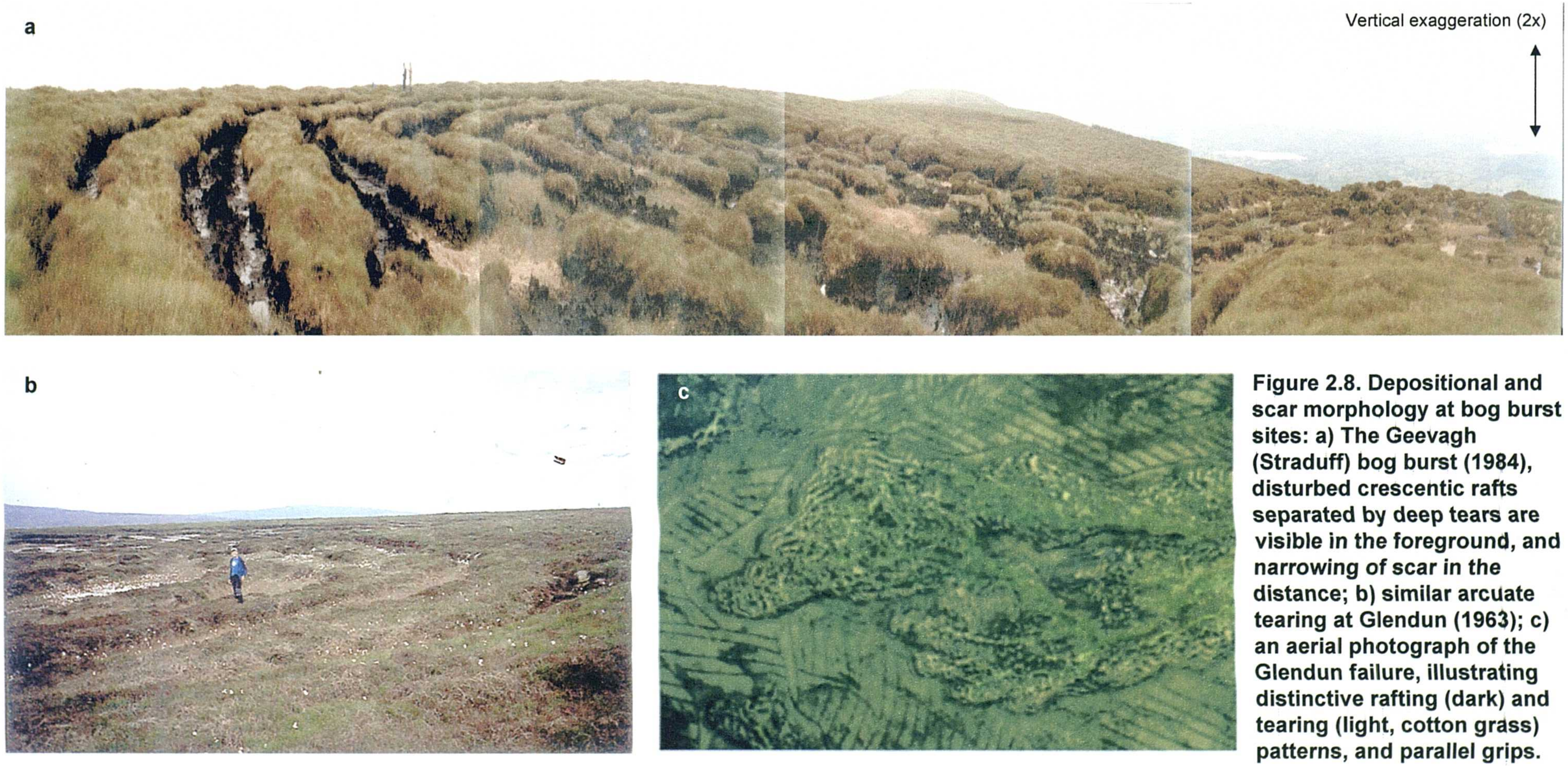


Figure 2.8. Depositional and scar morphology at bog burst sites: a) The Geevagh (Straduff) bog burst (1984), disturbed crescentic rafts separated by deep tears are visible in the foreground, and narrowing of scar in the distance; b) similar arcuate tearing at Glendun (1963); c) an aerial photograph of the Glendun failure, illustrating distinctive rafting (dark) and tearing (light, cotton grass) patterns, and parallel grips.

shaped disturbance area (Tomlinson, 1981).

While blocks, rafts and the debris runout zones that develop are frequently cited as features in both bursts and slides, deep and extensive tearing is mainly confined to bog bursts. Honohane (1697, p715) describes 'large chasms and great cracks' throughout the surface of a failed bog in Ireland. Praeger (1897) notes concentric fissures around a burst margin in County Kerry, and Alexander *et al.* (1986, p110) report the 'heavily crevassed' upper source area of a burst in Sligo. The upwelling of great masses of sludge (Praeger, 1897, p151) or 'semi liquid basal peat' described by Alexander *et al.* (1986, p110) contrast with Delap and Mitchell's (1939, p196) account of a peat slide (reported as a burst) in Wicklow:

> '...large cracks were to be seen around the upper margin, but they did not extend to any great distance, nor had they any regular arrangement. There was no welling up of soft peat beneath the cracks...'

The slurried outflow of peat described above is assumed to have its origins from below the let-down surface material (Griffith, 1856-1857; Praeger, 1897; Cole, 1897; Delap *et al.*, 1932). However, as with peat slides, it is possible that some peat slurry is generated during the motion of larger debris. This slurry is frequently described as transported in the swollen stream systems that characterise flood events with which bog bursts are associated (Figure 2.9). The presence of a 'trashline' left by this type of deposit has been described by many authors (Latimer, 1897; Colhoun *et al.*, 1965; Alexander *et al.*, 1986). In some cases it may form a visible morphological relict for several years before being eventually washed away (Praeger, 1906; McEwen and Withers, 1989).

The distinctive morphology of bog bursts has led a number of authors to map the features in the field. Examination of some of these maps illustrates quite well the key morphological components described previously (Figure 2.8). Comparison of aerial photographs of peat slides (Figure 2.11) with maps, ground and aerial photography of bursts (Figures 2.12, 2.10 and 2.8c) illustrates the differences between the two feature types.

Definition of bursts is somewhat more consistent than slides, though again 'flow' and 'burst' (and even 'slide') appear to be regarded as fairly interchangeable terms. Confusion in terminology extends to consideration of process, as evidenced in a report by McEwen and Withers (1989, p150):

> '...documented bog bursts have been subdivided into translational peat

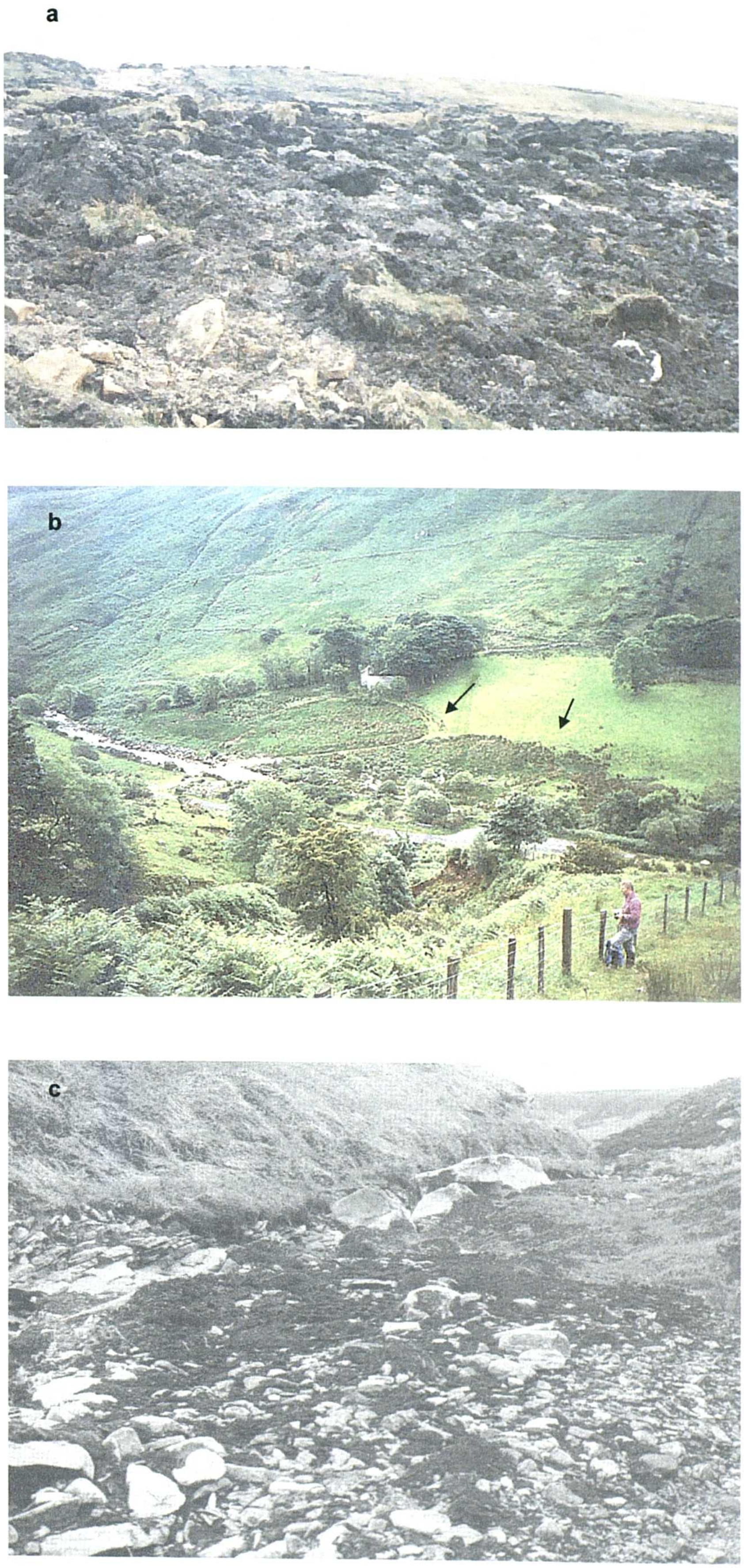


Figure 2.9. Peat failure trashlines: a) slurry on scar at Nein Head II (taken 3 months after event); b) vegetation change marking former trashline of Glendun failure (taken 35 years after event); c) slurried deposit left in coupled channel below Boulsworth Hill (North Yorkshire) taken shortly after event (Evans, 1993)

Figure 2.10. Slieve-Rushen bog burst (Co. Cavan, 1965): a) crescentic tearing visible in foreground, pond in background (arrowed) marks front of compression ridge of deposit; b) compression ridge visible behind cotton grass in middle ground.

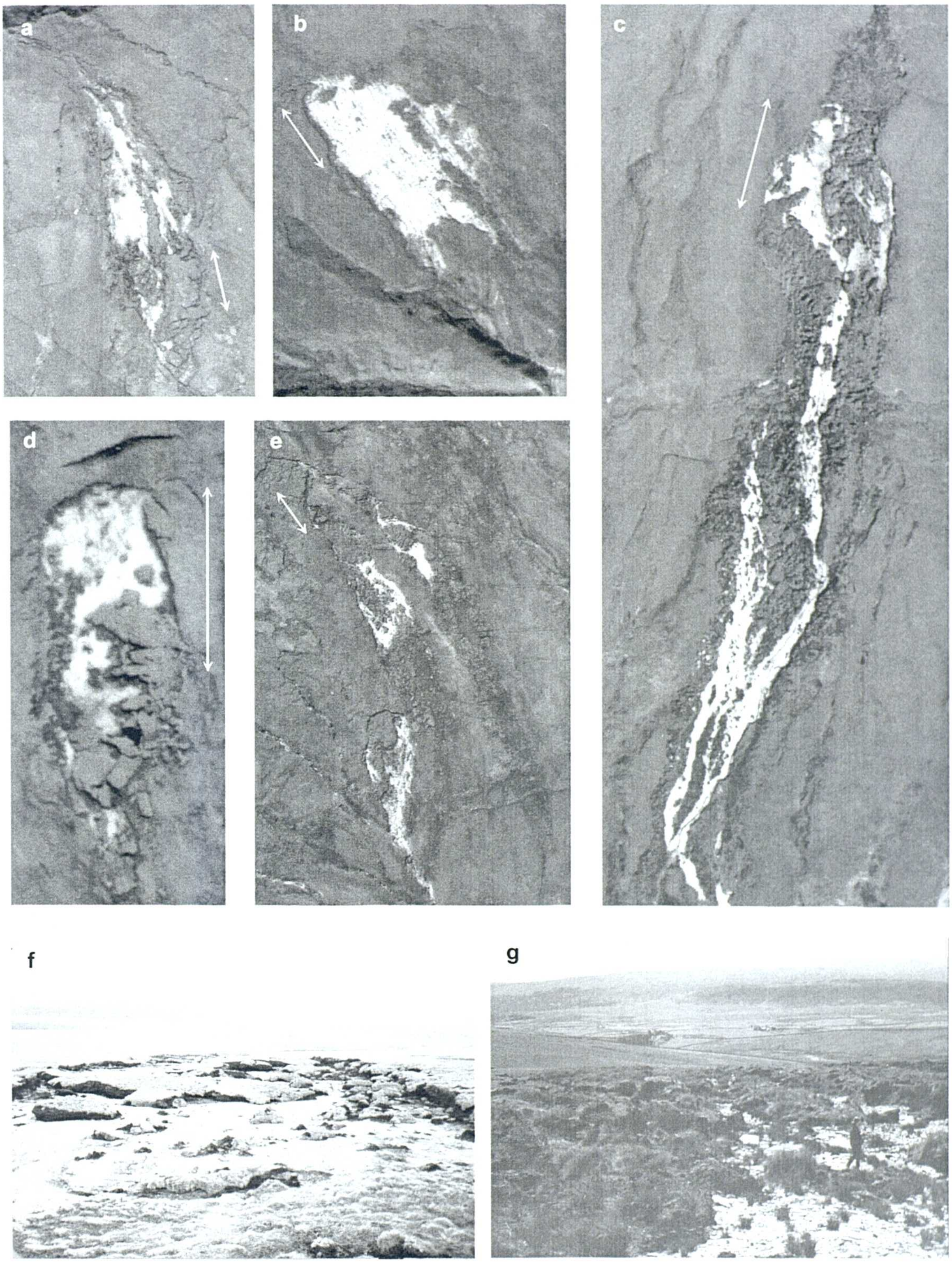


Figure 2.11. Aerial and ground photography of peat slide failures. The white scale arrow corresponds to approximately 50 m on all aerial photographs: a) Langdon Head (1983); b) Middlehope Head (1983); c) Hart Hope (1995); d) Nein Head 3 (1983); e) West Grain (1983); f) Nein Head 3 head scar area with blocks, rafts and excavated scar; g) Hart Hope scar with stranded blocks.

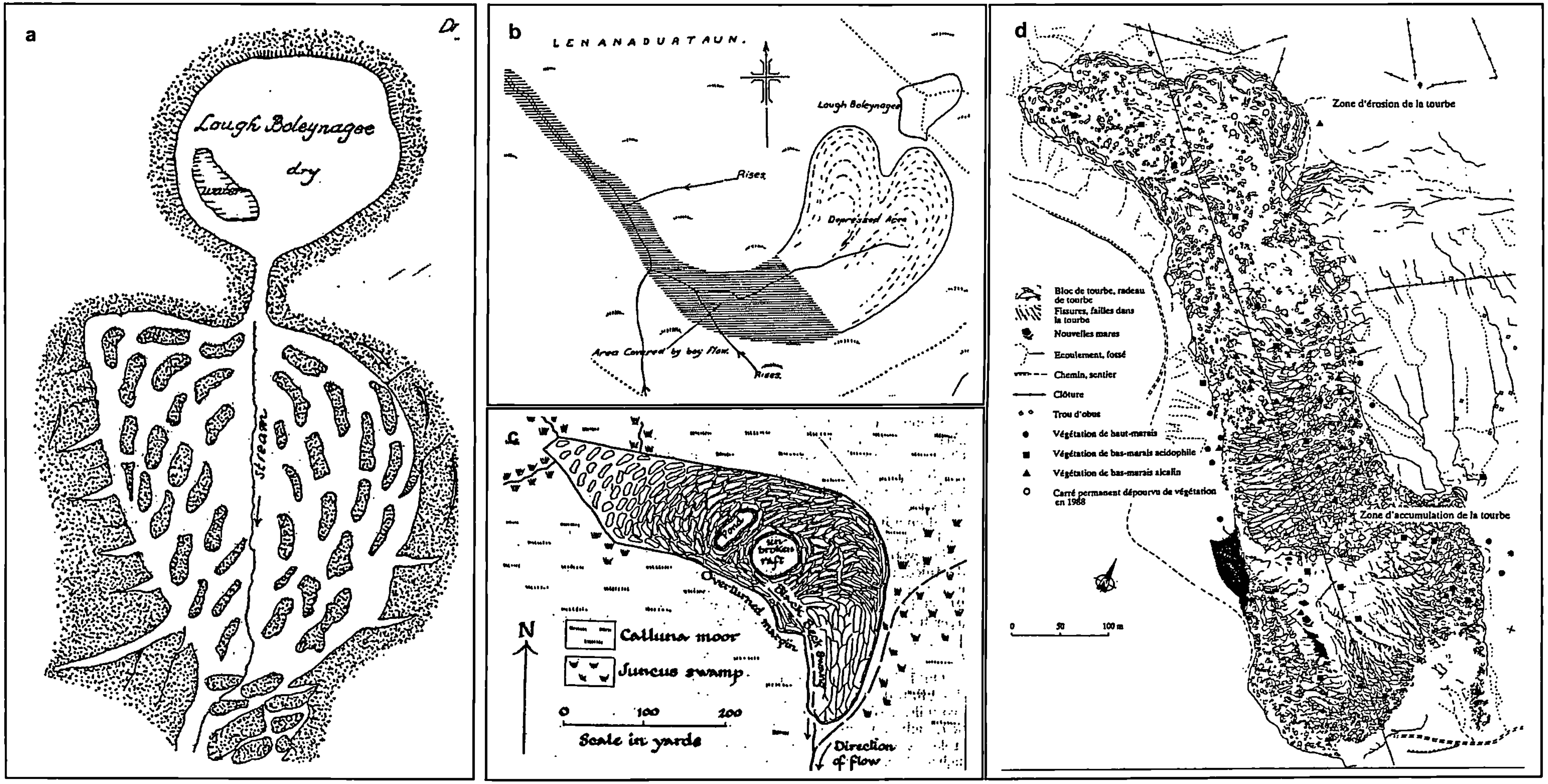


Figure 2.12. Bog burst field mapping: a) Glencullin bog burst mapped by Osvald (reproduced in Feehan and O'Donovan, 1996) and b) by Delap *et al.* (1932), both clearly illustrating concentric and arcuate nature of tearing and rafting; c) Danby-in-Cleveland bog burst (1938), reported by Hemingway and Sledge (1941-1945), arcuate tearing and rafting without clear scar area also evident; d) La Vraconnaz bog burst (1987) mapped by Feldmeyer-Christe (1995), illustrating arcuate rafting and peeling away in upper source area, and deposit jam in lower slope.

> slides and gullying occurring on steeper slopes, and bog flows within ombrogenous mires associated with an unconfined flow of liquid or semi- liquid peat…'

Some of the difficulty in separating bursts and slides by morphology may relate to the presence of indistinct forms. In these cases, the absence of evidence corresponding to previously published examples has led the authors to chance their arm with definition. For example, Colhoun (1965) categorised an event in County Cavan, Ireland, as a burst, despite citing the presence of a 'slip plane', and an absence of release of slurried basal peat. A visit to the site undertaken as a contribution to this thesis revealed morphology consistent with the majority of bog bursts described previously. It is possible therefore that field evidence of slurried peat had disappeared by the time of Colhoun's survey. Bishopp and Mitchell (1946), and Delap and Mitchell (1939) described similar failures with slip planes within the peat mass and an absence of evidence for slurried basal peat deposit. These were termed bog 'flows', though the term implies fluidity in movement over the more rigid sliding mechanism they cite in failure. The examples highlighted by Wilson and Hegarty (1993) in the previous section, in which the failure plane was located within the peat mass may also have been defined as bog bursts or bog flows by these earlier authors had they happened across the features.

Field morphological evidence in this and the previous section suggests that most examples of peat slides and bog bursts have characteristically differing arrangements of related morphological features (cracks, tears, peat masses, zones of excavation and disturbance). However, there exist a limited percentage of features in which categorisation is difficult. This would suggest that peat slides and bog bursts occupy the ends of a spectrum of related processes involving mass movement in peat. The following section considers the issue of peat mass movement definition in the wider mass movement context.

2.2.3 Classification systems for mass movements and peat mass movements

Conflict in both classification and terminology is a common theme in mass movement studies (Selby, 1993; Dikau *et al.*, 1996). This applies to both the morphologies involved, and the mechanisms responsible for them. Crozier (1986) has noted that unchecked proliferation of classification schemes defeats the object of classification or definition, namely the provision of clear and unambiguous terminology. This applies even within the relatively narrow range of processes and forms described in peat mass movement literature. As highlighted previously, the terms 'peat slide', 'bog slide', 'bog burst', 'bog flow', 'peaty-soil flow' and 'peat flow' have all been used to describe mass movement processes in different types of peat. In some cases, two different definitions have been applied to the same event, such as in the case of the Yellow River peat slides (Coxon *et al.*, 1989), also known as the Slievenakilla bog burst (Large, 1991). The use of the term 'bog' over the word 'peat' implies that the event occurred in either raised, valley or blanket bog, rather than any other peat deposit. Consideration of peat slides and bog bursts should not confuse the issue of definition further by creating new terminology specific to material type, e.g. 'peat burst' or 'mire burst', nor should it perpetuate unpopular existing terminology such as 'bog slide'. Discussion through the remainder of this thesis will continue the use of the terms 'bog burst' and 'peat slide' within the broad morphological definitions described previously. Whether a feature is a 'slide', involving a distinct slide mechanism in initiation, or a 'burst', involving a catastrophic release of fluidised material, is a matter for case-by-case classification of individual features. On the whole, morphological description of 'slides' relative to features known as 'bursts' suggests there are certainly process distinctions between the two.

Few existing mass movement classifications consider either bog bursts or peat slides within their frameworks. There are four widely used schemes, the process based classification of Sharpe (1938), the process and material classification of Varnes (1958), Hutchinson's (1977) morphological classification (in Crozier, 1986) and Crozier's (1973) morphometric classification. Neither Sharpe's nor Varnes' schemes include peat failures, as the former excludes materials and the latter excludes organic soils. 'Bog' slides, flows and bursts are all included under the 'translational slides' section of Hutchinson's classification, with this potentially inappropriate amalgamation of differing process types corrected in his later expanded scheme (1988). Jones and Lee (1994) also grouped peat slides and bog bursts together, despite their process based distinction of UK landslide types. Where separately defined (Hutchinson, 1988; Crozier, 1986), peat (bog) slides have been considered as translational slides, and bog bursts as fluid or viscous flows. This viewpoint is summarised in Figure 2.13, which provides a framework for peat mass movement definition based on the morphological evidence and related processes described in the previous sections. Peat slides and bog bursts are considered as distinct but related events with characteristic but overlapping forms and processes. Initiation mechanisms are assumed to differ, but ultimately a flowing transport mechanism dominates both failure types.

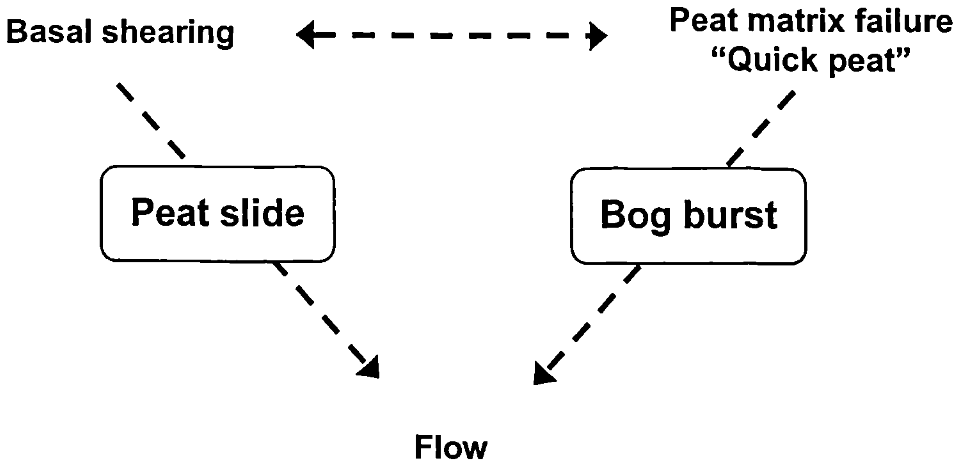


Figure 2.13. A framework for peat mass-movement definition. Peat slides and bog bursts are seen as two separate morphologies, the former initiated by basal shear, and the latter by collapse of the peat matrix. The initial failure processes may tend towards flow once movement has initiated for both failure types. It is expected that there will be composite failure conditions that may produce intermediate landforms.

Failure Mechanism	Description	Material control	Examples
Shear failure by loading	a) Increase in overburden by drying/capillary tension, or by fresh snowfall	shrinkage rate, bulk density, hydraulic conductivity, porosity of upper peat layer	Hart Hope, Slieve-Rushen
	b) Increase in shear stress - hydrostatic pressure generated by water-filled cracks, ponds and lochs	shear strength of lower peat layers	Isle of Lewis, Skerry Hill
	c) Catastrophic loading - rapid increase in peat mass exceeds shear strength	shear strength of lower peat, overburden pressure	Birkbeck Gill, Dow Crag, Bloodybush Edge
Buoyancy effect	a) Generation of artesian pressures	seepage, permeability, porosity in basal peats, clays	Nein Head, Danby-in-Cleveland, Langdon Head
	b) Increase in interstitial pore-water pressure and reduction in cohesion	seepage, permeability, porosity, clay content of basal peats	Bilsdale, Hermitage Water, Slieve-an-Orra, Haworth
Lubrication	a) Basal peat slurried by increased water content (passing of liquid limit)	atterberg limits, permeability of basal peat	Flat Creek, Green Gorge, Feldon Burn,
	b) Basal clay slurried by organic acid dispersal (passing of liquid limit)	clay disaggregation by humic/fulvic acids	not available
	c) General increase in basal moisture content by artificial drainage routing	seepage, permeability, hydraulic conductivity of basal peat and clay	Carntogher, Bellacorrick, Owenmore
Surface rupture	a) Swelling of basal peat ruptures drier surface, releasing it	porosity and storage of lower peat (amorphous/granular)	Glendun, Barnesmore
	b) Relative swelling of basal peat by contraction of surface during drought	shrinkage of upper peat (fibrous)	Glencullin
	c) Long term depth creep inducing surface rupture or shear failure	clay content of basal peat, strain weakening	Moanbane
Margin rupture	a) Removal of underlying support by stream action, with basal peat release	tensile strength of peat restraining walls	Killanena, Powerscourt
	b) Removal of underlying support by cutting, with basal peat release	tensile strength of peat restraining walls	Knocknageeha

Table 2.3. Material controls on existing perceived failure mechanisms (refer to Figures 2.2 and 2.3 for locations and dates of failure)

2.3 Landslide initiation and mechanism: the processes of peat mass movement

There is an extensive literature that discusses mass movements and slope stability. This section reviews published theories of peat failure mechanisms, summarising them in a form appropriate to consideration within established landslide process frameworks. Subsequently, in the light of form and process evidence for the differentiation of peat slides and bog bursts, the classificatory framework defined in section 2.2.3. will be justified as a basis for the remainder of this study.

2.3.1 Peat slide failure mechanisms

In terms of peat slides, discussion has focused on the location of the failure plane or slip surface involved in translational failure, on the climatic triggers, and on the hydrological effects of these triggers. Factors contributing to failure are summarised in Table 2.3, and described below.

Crisp *et al.* (1964, p525) describe three peat slides in the North Pennines, whose trigger '*...was the failure of the clay-peat interface and the [failure of the] surface vegetation to withstand this strain*'. Shear failure is not cited, but a reduction in basal friction through water action is postulated. Similarly, Johnson (1992) describes a slide with a failure initiating at a clay-peat interface, fed by spring water from a sandstone band in underlying clay, and by infiltration of water through surface tears, although no failure mechanism is suggested. Carling (1986) cites a combination of high pore-water pressures (Table 2.3, 'buoyancy effect'), upward groundwater gradients and strain-softened clays as causative of five large slides, also in the North Pennines. However, shear failure *within* the clay is regarded as the ultimate cause, and a simple stability analysis has been undertaken. Failure within an indurated ferruginous layer beneath a peat-clay interface was noted for a set of several slides occurring in Scotland in 1983 (Acreman, 1991). High pore-water pressures were suggested as the probable cause of the multiple failures, created within the clay by impeded drainage from the impermeable ferruginous layer. Wilson and Hegarty (1993) describe morphology distinct to peat slides for two events in Co. Antrim, with failure planes within the bottom 10-20 cm of the peat mass, the depth of which appear to be defined by a clear textural discontinuity. They hesitantly suggest shear failure encouraged by water entering the basal layers via creep-induced cracking, but concede that a lack of knowledge of the peat conditions around the time of failure prevent any further elaboration. Tomlinson and Gardiner (1982) note seven slides in the same county, occurring between a sandy-clay and an organic rich overlying clay (possibly a transition peat). Other than the influence of high infiltrated rainfall, no distinct mechanism is suggested. Hendrick (1990) produces an unexplained stability analysis for a bog burst in Co. Kerry fed by collector drains, with shear failure as the mechanism (Table 2.3, 'shear failure by loading'). Coxon *et al.* (1989) describe a multiple peat slide event near the Yellow River in Co. Leitrim, but do not suggest a failure mechanism. They cite high rainfall as a causative factor, as does Large (1991) who describes the event as a bog-burst, failing to propose any form of failure mechanism.

In these examples, it appears that increases in moisture content, usually near the peat/substrate interface are the main control upon failure. In the case of shear failure, water may act to reduce the shearing resistance of the peat, substrate, or interface in three ways. Firstly, loading of the basal material by saturation of the *overlying peat* or by weight of snow (Colhoun, 1982; Warburton and Higgitt, 1998) may exceed the frictional shearing resistance of the soil and cause it to fail (Landva and Pheeney, 1980). This process would be most likely to occur in the peat substrate (Carling, 1986), as the concept of tensional rather than frictional resistance is favoured for the cellular structure of peat by many workers (Helenelund and Hartikainen, 1972; Wilson, 1972). For example, raised water contents within peat, whilst reducing interparticle cohesion, would not greatly affect fibrous tension. Shear stresses may be generated at depth by the presence of hydrostatic loads acting horizontally from infilled cracks, ponds and artificial drainage lines (Clough 1888; Bowes, 1960; Wilson and Hegarty, 1993). Selkirk (1996) suggests possible seismic triggers for slides on Macquarie Island, in which the material strength of the peat and substrate is reduced by sequences of vibration induced by earthquakes. Finally, some earlier reports of peat mass movements have suggested a hydraulic mining effect caused by force of rain upon the bog surface (Mushchamp-Perry, 1897; Hudleston, 1930). In these cases, it is suggested that the velocity and magnitude of water impacting the peat surface would be sufficient to scoop the material from the substrate. The physical basis for such a mechanism is not considered, and it is unlikely that rainfall, even as a 'cloudburst' would be of sufficient magnitude in the North Pennines (if anywhere) to achieve such an effect. However, extreme climatic events such as cloudbursts are often cited as triggering mechanisms. In most cases, cloudbursts (or intense showers of short duration) are described in conjunction with peat failures, slides as well as bursts (Muschamp-Perry, 1897; Hudleston, 1930). Frequently, the term 'waterspout' is used to refer to the climatic and geomorphic event as a whole. Kinahan (1897) in a summary of failures to the end of the 19th century, also noted the association of high and 'cutting' winds with bog bursts in Ireland. Climatic preparatory and triggering mechanisms are examined further in

Chapters 3 and 6.

Alternatives to shearing may involve increases in basal moisture contents, inducing buoyancy effects or liquefaction of the basal material (clay or peat) to produce a zone of failure, rather than a shear plane (Table 2.3, 'buoyancy effect'; 'lubrication'). Caillier and Visser (1988) have observed the effects of long-term disaggregation of clays by humic substances, and this may operate at the base of peat blankets. Carling (1986) has described the build up of artesian pressures in the lower slopes of failures in the Pennines. Gilman and Newson (1980) have noted the presence of pressure build up in pipe networks in peat catchments in Wales, while Hobbs (1986) notes that in the presence of gas associated with the decomposition process, peat of over 500% water content may be buoyant under water. On a micro-scale, the disruption of cell structure by loading, creep or seepage pressures (Mitchell, 1938; Wilson, 1972; Crozier, 1986) may act to transfer water held within plant cells into the void water, increasing pore-water pressures and buoyancy effects (Glynn *et al.*, 1968).

Many of these processes may not be mutually exclusive, and it is the combination of causes and mixed use of terminology that often clouds the discussion of mechanism in both failure types. Poor understanding of peat slide mechanisms may in part stem from lack of information about the peat-clay interface. This interface may range from a very sharp boundary over a few millimetres in depth to an indistinct transition over several centimetres. This boundary in itself will vary spatially throughout a slide location, so that a failure plane of uniform characteristics is unlikely to exist. Furthermore, where slides have been subject to heavy rainfall and erosion by the moving material immediately subsequent to failure, the failure surface may be quickly washed away or modified, and incorrect assessments made of its location by visiting fieldworkers. The difficulties inherent in geotechnical testing of transition peats, fibrous and stony clays, and amorphous peats, also complicates different failure scenarios.

2.3.2 Bog burst failure mechanisms

Accounts of bog bursts almost always focus on the failure of a basal layer of liquid or semi-liquid peat. The mode and time-scale of development of this layer is rarely discussed, but the nature and consequences of its release are frequently narrated. During the preparatory phase, water is transferred to the basal layer, or peat state alters as a result of creep or other unspecified processes. The trigger for movement may relate to the crossing of an internal threshold of stability, for example through reduction in material strength, or through an externally governed response to a geomorphic trigger, such as fluvial undercutting and removal of the blanket margin, followed by release of the fluidised material (Table 2.3).

Colhoun *et al.* (1965) cite a number of causes for the largest recorded bog burst in Ireland, at Glendun, in Country Antrim. Among these are pressure build up in lower semi-liquid peat and surface rupture, self-loading to failure after heavy rainfall, and depth-creep induced tearing of upper layers, again with basal peat release (Table 2.3, 'surface rupture'). None of these are mutually exclusive, although common to all peat failures self loading by increased water intake seems unlikely, as the already saturated peat mass will change little in weight with extra rainfall. Colhoun *et al.* (1965) also suggest the potential effects of depth-creep in remoulding basal material to trigger a 'reversal of phase' (Bishopp and Mitchell, 1946, p153). The timescale over which this might occur is not specified, though both the very short term and the long term have been suggested. Equally, the changes in moisture content necessary to trigger a change in phase may be very small. Hobbs (1986) notes liquidity ratios of peat very close to those of Norwegian quick clays whose failures are morphologically similar to bog bursts.

In the Geevagh burst (Figure 2.8a), County Sligo (Alexander *et al.*, 1986, p118), no failure mechanism is suggested although the failure appears to have initiated as a margin rupture, heavy rainfall having percolated through to the deeper peat and overloaded a bounding peat wall downslope (Table 2.3, 'margin rupture'). Low bulk densities and high moisture content suggest a buoyant and potentially fluid basal material. Failure is suggested where a lower amorphous peat '*...absolutely without coherence...*' exerts pressure on a drought-responsive shrinking upper-fibrous peat, and surface tearing allows the release of the lower layer. In an eyewitness report, failure is described as retrogressive, surface rupture having '*...spread rapidly back up the hill and outwards...*' initiated at a spring fed seepage point downslope. The basal layer is described by the authors as '*...water with peat in suspension*', rather than '*...peat with absorbed water*'. The propensity for peat to swell with increasing moisture content, and shrink on drying has been noted by a number of authors (Ingram, 1983; Price and Schlotzhauer, 1999), with variations in peat profile depth of up to 10% noted (Price and Schlotzhauer, 1999).

Mitchell (1935) alludes to long term deformation effects in describing a burst in County Clare. Here, he describes a blanket margin rupture resulting from the slow downslope 'flow' of very humified basal layers. With the effective 'unplugging' of the blanket, rapid remoulding may take place of already strain weakened basal peat, and outflow and subsidence initiate. Kinahan (1897) suggests a different origin for fluid basal layers in bogs. He argues for the formation of 'shaking bogs' (or 'floating' and 'quaking' bogs; Price and Schlotzhauer, 1999*)* by surface encroachment of vegetation over existing spring-fed water bodies, which may lead to buried water masses. Conversely, the connection of networks of sub-surface pipes, and their supercharging may create enough basal water to permit burst-type failures. Here, the potential crossover can be seen between detachment failures in slides and subsidence failures in bursts.

Finally, anthropogenic triggers have been associated with a number of bursts in Ireland. These usually involve drainage, often with respect to the effects of cutting, in providing an initial surface or margin rupture (Cole, 1897; Praeger, 1897; Tomlinson, 1981). On occasion however, the importance of drains in destabilising peat masses has been associated with longer-term changes in hydrological regimes. These centre on blocked drains increasing the water quantities of previously drained peat (Carling, 1986; Hendrick, 1990), or the effects of drainage in drying surface layers, with associated cracking and provision of access routes for water to the basal peat layers.

2.3.3 Causal factors for peat mass movements

As the previous accounts illustrate, two main themes dominate the study of peat mass movement processes. These are the conditions which prepare the slope for failure, and the processes by which failed slope material is transported (Crozier, 1986; Selby, 1993). Slopes may be considered as stable, marginally stable (unstable) or actively unstable (Crozier, 1986; Dikau *et al.* 1996). Stable slope materials are resistant to all destabilising forces (e.g. gravity, pore-water pressure, fluvial undercutting) acting upon them. Marginally stable slopes may fail if a certain level of activity is achieved by these forces (or stresses). Actively unstable slopes have 'failed' to resist the activity of these forces, and experience movement either continuously or intermittently. The intrinsic properties of the slope material that act to resist instability are represented by the material's shear strength. The balance between stresses and strength form the basis of slope stability analyses. Causal factors in peat mass movements relate to either the reduction in strength of the material, or increase in stresses upon it.

Figure 2.14 considers the stresses (or forces) that have been implicated as causes of peat mass movement in the literature. They may be divided into those which prepare the slope for failure in the long term (preparatory), those which cause the strength of

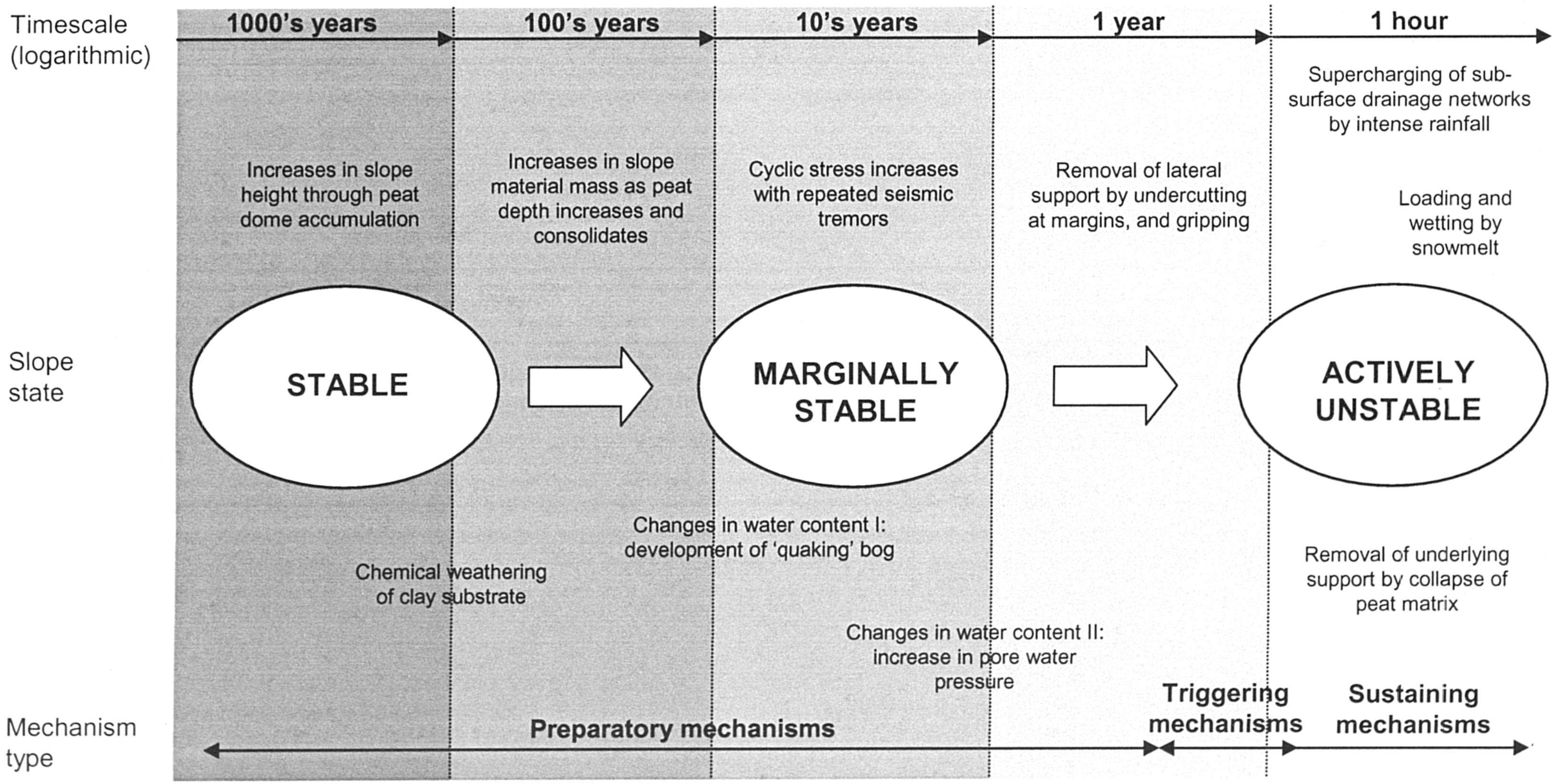


Figure 2.14. Causal and temporal framework for peat mass-movements: preparatory, triggering and sustaining mechanisms are placed in their appropriate causal and temporal framework (after Crozier, 1986, but adapted for peat).

the material to be exceeded and which act in the short term (triggering), and those which cause movement to continue once failure has initiated (sustaining). In peat environments, long term preparation of a slope for failure may relate to increases in slope mass through growth of vegetation (i.e. continuing peat accumulation) and incremental loading via the accumulation of colluvial debris from further upslope. Reduced shear strength may result from changes in the physical structure of peat or substrate, as a consequence of creep and fracturing, or dispersion of clays by peat-substrate chemical reactions. Alterations in slope geometry, related to disparities in accumulation rates between central and peripheral blanket areas (Ingram, 1982) may reduce stability over 10^2 - 10^3a. In the shorter term, instability may be caused by changes in moisture content of the peat mass, chemically induced loss of strength of underlying peat or substrate material, physical remoulding and buoyancy. Seismic weakening of intergranular bonding forces in the long term and seismic loading and horizontal acceleration have been implicated in the short term for some peat failures (e.g. Selkirk, 1996). Removal of lateral support, particularly by channel erosion and by human agencies has been associated with burst failures in particular. Triggering mechanisms may relate to the smallest change in moisture content, loading or shear strength at the end of an extended period of slope preparation, and thus may represent a tiny fraction of the sum of transient forces experienced by a slope through time, even though they are the ultimate 'cause' of failure. This has quite rightly lead to the suggestion that calling the final factor the cause, is like calling the match that lit the fuse that detonated the dynamite that destroyed the building *the* cause of the disaster (Schuster and Krizek, 1978).

Separating triggers from preparatory factors in the short term is difficult (Schuster and Krizek, 1978; Crozier, 1986; Jones and Lee, 1994). The consideration of preparatory and triggering factors in peat mass movement literature normally focuses on long term basal deformation by remoulding of the peat mass in the case of bursts, and shorter term triggering through exceptional climatic events (heavy rain, or snowmelt) in the case of slides, and bursts. Long term slope preparation is rarely considered for peat slides. Instead, the assumption of a shear failure mechanism has attracted the application of slope stability analyses as an explanatory tool for slope preparation. This is despite the misgivings about its application to organic materials.

The impact of the failure on local systems depends on the extent to which failed material is transported, or on the 'runout' of the failure. The nature and controls of runout have been subject to limited discussion in the context of peat mass movements. In the cases of both peat slides and bog bursts, it has been suggested that after initial failure, flow of material becomes the dominant process. Peat slides, following the sequence suggested by Selby (1993), below, are likened to translational slides in initiation (or debris slides) developing into partly liquefied or slurried (Hungr and Evans, 1985) debris flows in their lower portions. As such, the processes operating in these stages are all of relevance in the study of peat slide sediment dynamics.

> '...initial failure is usually by rotational failure or translational sliding followed by bending of the sliding slab, with tensile cracking as the slab moves over hummocks or over the lip of the slide scar...viscous fluid behaviour develops as down-slope velocity increases and shear resistance declines...'
>
> Selby (1993, p305)

Much of the runout zone of peat slides is defined by a coverage of solid blocks and wet debris (or slurry). The balance between the two types of deposit reflects the rheological processes acting immediately prior to deposition at any point on the slide. It may be assumed that areas dominated by sliding are characterised by an abundance of solid material, relative to those governed by flowing. In bog bursts, where the quantity of fluidised material is assumed to be greater, flow is expected to dominate over sliding, with the implication that runout may be more extensive. In this thesis, the term 'peaty debris flow' will be used to refer to the block and slurry deposit areas found at most slide and burst sites. This follows recommendations by Selby (1993, p302) in keeping with rheological terminology, but allowing breadth of consideration of process. It also corresponds with the use of the term 'peaty debris flow' by other authors in the field of peat mass movements (Campbell, 1981; Coxon *et al.*, 1989; Warburton *et al.*, in press). Beyond these basic ideas, little is known about the composition of slurry, or the relative proportions of the solid and fluid peat deposit components. Ideas taken from outside peat failure literature suggest that volume of material, slope geometry and self-lubrication may all be important in the control of runout duration and extent (Bovis and Mears, 1976; Crozier, 1986; Campbell, 1989).

2.3.4 Peat slide and bog burst definition: criteria for further research

Published form and process information for peat slides and bog bursts suggests that there are reasonable morphological and mechanistic criteria that differentiate the two types of event. To summarise:

i) Peat slide failures initiate by translational sliding of a coherent peat mass over a slip plane parallel to the peat surface. Peat slide morphology consists of a predominantly excavated scar area, with transported material moving downslope as rafts, and then blocks of peaty debris. The greater the degree of transport, the less coherent the transported debris and the more the transport process corresponds to a flow mechanism. As solid debris breaks up, slurried debris begins to dominate.

ii) Bog burst failures initiate by release of basal fluidised material through margin or surface tearing. Bog burst morphology consists of large arcuate peat masses sunken into the voids left by the flowing slurried peat. An exposed scar area is rare to absent. Some of the more solid peat masses may be transported downslope as blocks of peaty debris, possibly by sliding, but again degrading rapidly with transport and approximating a flow mechanism.

The preparatory and triggering conditions for each type may be similar, but the failure mechanisms themselves may differ. These mechanisms may converge in the lower slopes of both slides and bursts to produce a mechanism known as bog flow. The relationship between slide and burst forms, and the processes that operate are summarised in the framework shown in Figure 2.13. It is likely that there exist composite failures that exhibit morphology and processes common to both failure types. It is also the case that there are similar features in less peaty soils and in non-peat soils. The range of forms and processes precludes the investigation of *all* aspects of peat failures in a thesis of this length. As a consequence, the remainder of this text is concerned chiefly with peat slides, but by necessity will make reference to bog bursts and to other related features. The final review section examines the 'recovery' of peat landslide scars, and the implications of this for the evaluation of peat mass movements in time and space.

2.4 Landscape sensitivity and blanket peat regeneration: the recovery of peat landslides

Geomorphologically, the significance of peat mass movements (in common with many forms of rapid mass-wasting) is threefold: the immediate impacts in terms of landscape disturbance and sediment delivery; short-term alterations of local geomorphic systems through the crossing of thresholds (e.g. alteration of channel pattern through short-term blocking of a river valley); and their significance as slope denudation processes. These latter influences represent the reincorporation of the landslide scar into the landscape in which it resides. Ultimately, processes of weathering and erosion will act to modify the morphological remains of a failure until it is no longer recognisable as a mass movement feature. Given enough time, some landslides may develop soil types and vegetation cover indistinguishable from their surroundings.

Within the context of peat mass movements, the duration of reincorporation into the landscape, or recovery is significant for a number of reasons. The first is embodied in the relatively small inventory of peat failures. For example, in the North Pennines there have been 14 reported peat slides during the last 150 years. It is not known whether this sample represents the full population of events over this timescale. The record may not be complete because some events may have gone unnoticed. More importantly, regeneration of a blanket peat cover through time may act to extinguish any evidence of past failures. Without the ability to quantify the rate of recovery of landslide scars in peat areas, it is impossible to be objective about the frequency of failures historically, and hence to assess their significance in a wider landforming context. The presence of peat slides as active denudational agents on Holocene timescales has already been alluded to by Ashmore *et al.* (2000) in the Outer Hebrides. Anomalous inwashed peat layers in accumulating valley bogs dating from between 1750 and 3000 years BP have been interpreted as the deposits of failures from hillslopes that continue to be affected by contemporary peat and mineral soil failures. However, the landforms left by their occurrence have long since been erased from the landscapes they would formerly have occupied. This necessitates an understanding of the processes that govern morphological smoothing, i.e. the processes of recovery.

Landscape sensitivity in peatlands may be considered in two main contexts: geomorphic sensitivity and ecological sensitivity. Consideration of landscape change in geomorphology revolves around the discussion of 'sensitivity', or the '... likelihood that a given change in the controls of a system or the forces applied to the system will produce a sensible, recognisable, sustained but complex response...' (Brunsden, 2001, p99). Concerning landslide scars, the significance of sensitivity relates to the ability of the disturbed area to return to an approximation of its original state, or recover. The recovery period may be considered as the total time elapsed from the cessation of mass movement activity, until the arbitrarily defined state of recovery (e.g. complete vegetation cover). Because of the complexity of ecological and geomorphological response, the establishment of a vegetation cover and peat depth similar in composition to pre-failure conditions is highly unlikely. The extent to which the disturbed locality does stabilise is governed by its response to subsequent anthropogenic and natural disturbance and environmental change (Milne and Hartley, 2001). The integration of geomorphological and ecological processes, particularly with reference to sensitivity, has been considered under the banner of geo-ecology (Gordon *et al.*, 2001).

Geo-ecology elaborates the links between soils, vegetation, climate and geomorphological processes (Gordon *et al.*, 2001). The range of processes operating post-event at peat mass movement sites lend themselves particularly to a geo-ecological approach. For example, the dominance of either soil erosion or soil development across a landslide scar may be dependent at any one time upon climate (rainfall, temperature), vegetation colonisation, nutrient cycling, grazing of vegetation, physical weathering of the scar surface, drainage development and chemical weathering of parent materials at depth. Gordon *et al.* (2001) suggest that there is an interdependence of habitat diversity on the nature and range of active and relict landforming systems. In peatland landscapes, this interdependence is implicit. The main geomorphological processes may only act upon peat once it has formed, and formation is a direct function of ecological activity. The functioning of geomorphological systems within peat is directly linked to the ecological systems that provide the peat deposit. For example, Huggett (1995) regards peat erosion as the 'ultimate manifestation of sensitivity' in peat landscapes, where ecological change initiated by air pollution results in the death of Sphagnum, and increased susceptibility to erosive forces (Bragg and Tallis, 2001).

The recovery of landslide scars in geomorphological settings other than blanket peat is well documented (Lundgren, 1978; Larsen *et al.*, 1999; Westerberg and Christiansson, 1999). Although most studies focus on translational slide scars, similar in scar morphology to peat slides, variations in climate, soils, relief and baseline conditions make generalisations about recovery pathways difficult. Post-failure recovery is shown to reflect the balance between geomorphological, pedological and ecological activity on each scar. Recovery is generally impeded by geomorphic activity, which includes sheetwash, rilling and ultimately, gully development (Larsen *et al.* 1999). In some cases, quantities of sediment exported post-failure may exceed that transported during the mass movement event itself (Lundgren, 1978). Stabilisation of the landslide scars by vegetation has also been investigated, usually in combination with early stages of pedogenesis (e.g. Pandey and Singh, 1985; Dalling and Iremonger, 1994; Zarin and Johnson, 1995). The colonisation of the scar surface is initially slow, often dependent upon a priming stage of substrate weathering and nutrient release (e.g. Trustrum and DeRose, 1988). The effects of forest litter, algae growth, exposure to sunlight as determined by scar relief, and the prevalence of creeping species have all been implicated in recovery rates.

The study of revegetation and recovery of peat mass movement scars is relatively rare. Within a long established literature reporting bog bursts and peat slides (more than 100 citations from 1689 to 2001), only a handful have focused on recovery. These refer to both 'slide' and 'burst' type morphologies. Praeger (1906) visited an historic burst 'seven years after' its occurrence and described the development of the site since failure. Vegetation development was minimal on the scar itself. The exposed sandstone/gravel substrate had experienced no initial colonisation, and only localised shoots of *Eriophorum vaginatum* could be found on bare peat deposits. Vegetation change had taken place on the dislocated rafts of peat however, with a change from grassy species to an assemblage dominated by heather. Drainage of the scar surface could be seen to initiate in the crevassed tears between rafts, though no incision of the scar surface was noted. The deposit trashline in the stream valley below could still be seen after seven years, an unusually long residence time for deposits of this type.

Large (1991) conducted more detailed studies on the Slievenakilla 'burst' (or 'Yellow River slides'; Coxon *et al.*, 1989) over a three year period. Quadrats and transects were taken over the deposit lobes and above the scars of two adjacent failures. The predominantly *Polytrichum commune/Sphagnum* species cover of the undisturbed blanket had become a *Juncus* dominated assemblage on the deposit lobes. Scar revegetation was not quantified however, as too little recovery was deemed to have taken place. In this respect, the study's focus on the predominantly stable deposit perhaps misses the point of recovery studies at these sites. Limited assessment of gullying and secondary scar-margin failures revealed that they were active processes at both failure sites. A later site visit as part of the research in this thesis revealed the feature to be of 'slide' morphology, as defined in section 2.2.1.

Adjacent peat slides of differing ages were compared by Crisp *et al.* (1964) on Meldon Hill in the North Pennines. Scars from two failures examined after only a few months were clear of any revegetation. An older scar, dating 90 years previously had experienced marked, though not complete revegetation. The surface was noted as wet, consistent with the presence of drainage lines or shallow soakways beneath the vegetation cover. Species associated with wet surfaces, such as *Eriophorum vaginatum* and *Juncus squarrosus* were the main colonisers of this older scar. Larger blocky deposits could still be observed along the former trashline following the stream below.

Comparable studies of peat landslides exist in the southern Hemisphere. Campbell (1981) noted mosaics of such features in thin peat soils on Campbell Island.

Morphologically similar failures could be seen in various states of revegetation on many of the eroding hillslopes found there. Selkirk (1996) noted a lead time for peat accumulation on several peat slides on subantarctic Macquarie Island. Even after 50 years, in a climate conducive to peat formation, a landslide scar in Hasselborough Bay demonstrated little revegetation and no peat development. Previous non-peatland studies have noted that the cooler the climate, the less rapid the vegetative recovery (Rapp, 1997).

Finally, the most detailed peat slide revegetation study to date focussed on a large bog burst in Switzerland at La Vraconnaz (Feldmeyer-Christe, 1995). 100 permanent plots (quadrats) studied over 6 years revealed slow and random patterns of colonisation on the bare scar area, and species dependent alterations in vegetation abundance throughout the disturbed peat area. Species requiring continually moist conditions were the most adversely affected, while dryer species requiring mineral soils were more stable after colonisation. Unsurprisingly, the 6 year period was deemed too short to identify any successional sequences.

Across all of these studies, both those specific to peatlands and those outside, there has been little application of standardised methodology. This includes a lack of regard for established ecological techniques in vegetation survey, only limited attempts to quantify soil erosion, and poor justification for the selection and determination of soil properties.

2.5 Introduction to Part Two: Gaps in Research and Knowledge

The previous sections have provided a review of the peat mass movement literature, setting both peat slides and bog bursts within the contexts of differing peat environments, peat erosion processes and mass movement processes. The review demonstrates the diversity of approach, and of form and process typology. It also demonstrates some of the limitations of prior research. This section outlines gaps in knowledge relating to morphology, mechanism and recovery of peat mass movements, and constructs a methodological approach suitable to the resolution of some of these issues. While a rationale for each method used is provided here, description of specific methodologies and procedures is restricted to the appropriate chapters.

Peat mass movements have been considered in terms of definition, on the basis of morphology and mechanism, and significance in terms of recovery in the landscape.

These subject areas provide an appropriate framework for identifying research gaps. Peat material properties, intrinsic to mechanism are considered within a mechanistic context. Scar recovery is considered in terms of the effects of disturbance of ecological, pedological and geomorphological regimes at individual sites:

Morphology:

i) Lack of clarity with regard to the morphological basis for distinguishing peat slides and bog bursts (section 2.2.1. and 2.2.2.);
ii) Lack of consistency in identification and recording of morphological attributes at slide and burst sites (section 2.2.1. and 2.2.2.);
iii) A need to identify form analogues for peat mass movements which may elucidate mechanistic characteristics (section 2.2.3.);
iv) A need to extend studies beyond an individual site approach (section 2.2.1. and 2.2.2).

Mechanism:

i) Uncertainty over relative significance of extrinsic (e.g. climatic) and intrinsic (e.g. excess accumulation) controls over stability of peat slopes (section 2.3.1. and 2.3.2.);
ii) Lack of data concerning duration and velocity of movement (section 2.3.3.);
iii) Uncertainty over spatial and temporal controls of process convergence (i.e. tendency to flow) once movement has initiated (section 2.3.1. and 2.3.2.);
iv) Lack of geotechnical data concerning the behaviour of peat materials under stress (section 2.1.1.);
v) Lack of consistency in approach to peat stratigraphy descriptions from site-to-site (section 2.3.1. and 2.3.3.);
vi) Need to clarify the location of the slip plane in mass movements dominated by sliding (section 2.3.1.);
vii) Requirement to clarify the mechanisms responsible and material controls of subsidence failure in bog bursts (section 2.3.2.);

Recovery:

i) Need to examine vegetation recovery in methodological frameworks acceptable within ecology (section 2.4);
ii) Requirement to examine pedological development (section 2.4);

iii) Need to identify post-event geomorphological activity, the relative significance of the event, and subsequent reworking (section 2.4);

iv) Requirement to successfully integrate peat mass movements into wider frameworks of peat degradation (be they natural or human-caused) (section 2.2.).

2.5.1 A methodological framework for the study of peat slide morphology, mechanisms and recovery

In selecting a methodological approach appropriate to the study of peat landslides, some lines of enquiry may be discarded immediately. Monitoring of geomorphological 'events' is not possible unless there is forewarning of their occurrence. This, as yet, has only been achieved in the photogrammetric monitoring of existing landslide locations, which still remain active (e.g. Chandler and Brunsden, 1995), and in which tension cracks and surface bulging provide an indication of oncoming failure. The technique is highly resource intensive and not practicable for blanket peat locations. In the absence of monitoring, reconstructive techniques and modelling may provide viable alternatives.

Reconstruction has formed an important basis of much peat mass movement research. This has ranged from simple inference of process sequence from depositional evidence (e.g. rafts and blocks) to the use of hydrological parameters in estimate of flow velocity of slurried material (e.g. Coxon *et al.*, 1986; Warburton *et al.*, in press). Clear morphological evidence of transport processes has been demonstrated in previous sections (2.2.1. and 2.2.2.), and this lends itself well to the use of reconstructive techniques (e.g. Mitchell, 1938; Wilson and Hegarty, 1993; Lewkowicz, 1990).

Modelling utilises simplification as a means of elucidation (Thorn, 1988). There are many examples of the application of models to mass movement events, including scale hardware models of debris flows (Major, 1998), and empirical-mathematical approaches to hydrologically triggered translational slides (e.g. Brooks *et al.*, 1993). The Mohr-Coulomb failure criteria, the basis for slope stability analyses, have been the main empirical-mathematical modelling approach to peat slides (Hungr and Evans, 1985; Carling, 1986; Dykes and Kirk, 2001). Where utilised, none have been validated to the extent that they provide meaningful predictions of slope instability, and their usage in the elucidation of peat landslide mechanism and morphology is suspect. Dykes and Kirk (2001) reinforce this view, suggesting that their application of SEEP/W to a peat slide in Northern Ireland is neither satisfactory in predicting the failure on which it is based, nor transferable to other similar event types and landscape contexts. De Ploey and Poesen (1987) propose the use of verbal-conceptual models in the understanding of hillslope processes. They suggest that the advanced state of knowledge required to adequately predict even simple physically based relationships mitigates against the effectiveness of empirical-mathematical models. It is proposed that in this thesis, verbal-conceptual models are used to formalise understanding of differing components of peat slide morphology, mechanism and recovery.

Irrespective of the methods used, a sample population of features is required upon which to employ the methodology. Given the variety of potential geological, climatic, topographic and material controls on failure, an ideal sub-set of the world population would involve a range of sites clearly within the definition of either peat slide or bog burst, of differing age (to permit comparison of stages of recovery) and subject to similar climatic and geological controls (allowing attention to be turned to the effects of topography and material). Such a sub-set exists within the North Pennine region of the UK, in which fourteen peat mass movements have been recorded over seventy years, all of which fall within the peat slide classification, and which experience similar climatic conditions, underlying geology and stages of peat blanket development. The only other regional clusters in the UK and Ireland are for failures that all occurred under the same climatic event or that are not definitively peat slides or bog bursts (e.g. Acreman, 1991; Wilson and Hegarty, 1993). There are no significant clusters reported elsewhere in the world (section 2.1.2.). The next section describes the specifics of the North Pennine study area, the slides of which form the basis of the field component of this thesis.

2.5.2 The study area: the North Pennine region

Geologically, the North Pennines comprise the most easterly part of the Caledonian ridge, running from the Vale of Eden in the west to dip gently east and under the North Pennine coalfield (Taylor *et al.*, 1971). This geological base, over which the upland moors and dales occur, is referred to as the Alston Block, and is bounded to the North by the Tyne Gap and to the South by the Stainmore Trough (Warburton, 1998). It peaks at 893 m in the west (Cross Fell) and largely consists of open moor above 450 m (Figure 2.15).

Solid geology is primarily Carboniferous in age, comprising interbedded sandy shales, jointed limestones and sandstones (Taylor *et al.*, 1971; Carling, 1986; Dunham, 1990).

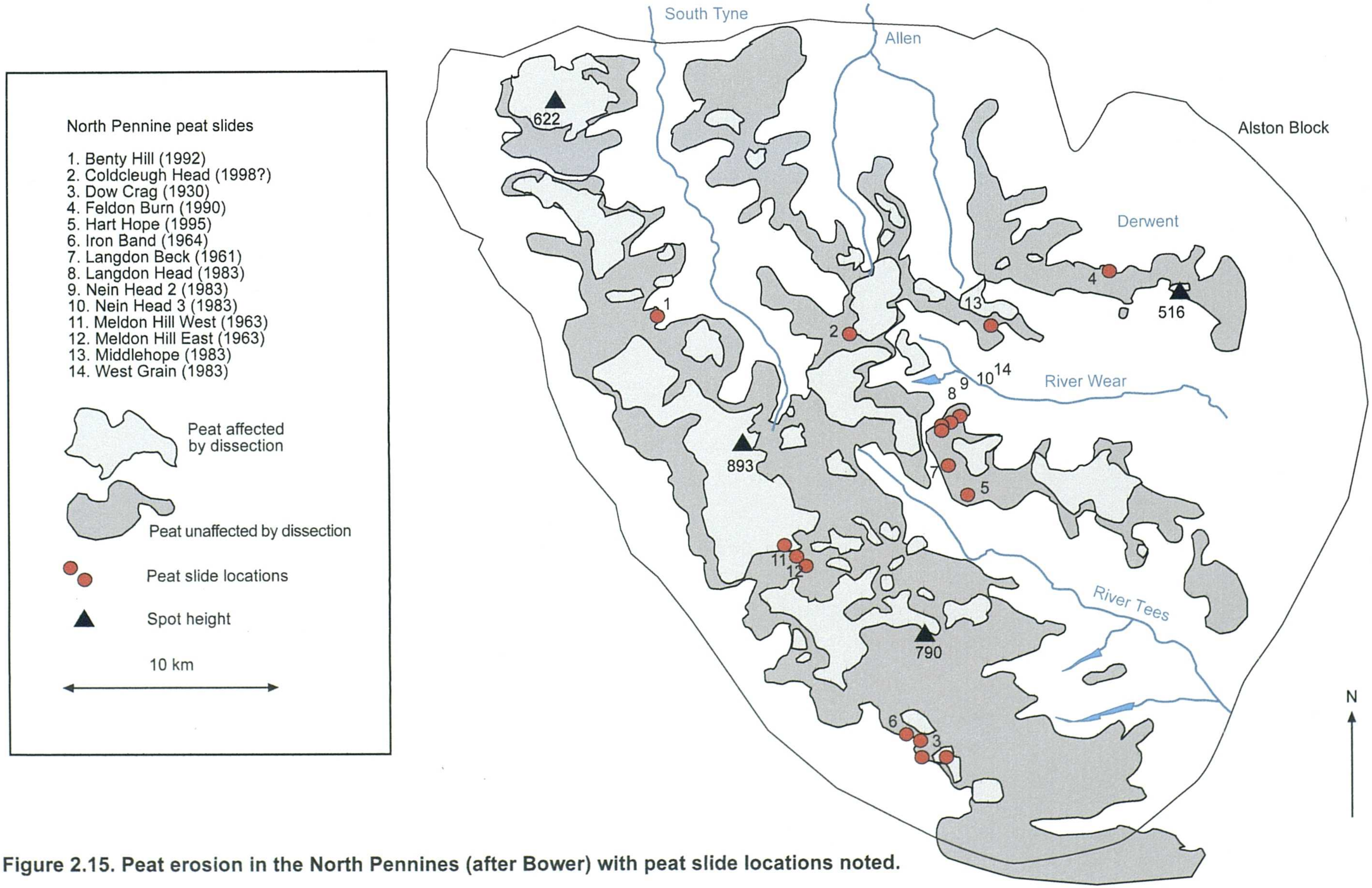


Figure 2.15. Peat erosion in the North Pennines (after Bower) with peat slide locations noted.

Both Carboniferous Middle and Upper Limestones contribute to small-scale strata outcrop springs in Weardale (Environment Agency, 1997), and to some extent in Teesdale. The influence of geology on landform development throughout the area is pronounced, with High Force on the River Tees, cutting into the Great Whin Sill, cited as a popular example (Taylor *et al.*, 1971; Warburton, 1998).

The hard rocks have been overlain and reworked to a large extent by Pleistocene glacial activity (Taylor *et al.*, 1971). A considerable thickness of glacial deposit, or till, mantles much of the North Pennines, most of which dates from the most recent, Devensian glaciation (Taylor *et al.*, 1971). The potential geotechnical instability of till has been cited by Bell (2000), and specifically for the Tees catchment by Bell and Coulthard (1991; Bell, 1998). The till material is often of high clay content, and is largely impervious (Environment Agency, 1997), contributing to poor drainage which in combination with high rainfall has led to the formation of ombotrophic blanket peat.

The onset and rate of peat formation has been variable across the North Pennines. At high altitudes where solifluction was active in the early Post-glacial period, early peat deposits were intercalated with reworked till layers (Pearsall, 1950), forming a basal layer of peat differing from the more widespread accumulations of the later Holocene. At lower altitudes, from 7000 BP, there commenced a period of forest growth and general decline in geomorphological activity (Warburton, 1998). Subsequently, around 3800 years BP, forest areas thinned largely due to human activity, and peat began to form in Teesdale (Pounder, 1989), and elsewhere in the North Pennines (Taylor *et al.*, 1971). Bog growth continued to develop apace with increasing humidity from 3200 years BP, until entering a stage of gradual deterioration from 2500 BP (Pearsall, 1950).

The North Pennine bogs reach thicknesses of up to 2.5 m, but vary in character from west to east. Pearsall (1950) attributes much of the eastern bogs to the rapid phase of accumulation in the later Holocene, and cites the western bogs as a product of earlier growth. The generally high spatial variability in bog development (Clymo, 1984) precludes an in-depth discussion of peat formation. Nevertheless, it should be noted that peat material properties are to a great extent a function of their depositional environments (Moore, 1986; Hobbs, 1986; Bell, 2000), and hence that variability in accumulation rates across the North Pennines will be manifest in differing material properties from site to site.

Together, the characteristics of the peat substrate and of the overlying peat mass determine the surface stability of slopes in the North Pennine peatlands. While the peat

Table 2.4. Surficial geology characteristics of North Pennine peat slides

Slide site	Peat mass characteristics*	Underlying substrate	Solid geology	Cited geological controls	Author
Benty Hill	blanket peat	till	Sandstone and grit	unpublished	n/a
Coldcleugh Head	blanket peat	till	Sandstone and grit	unpublished	n/a
Dow Crag	blanket peat	till	Carboniferous limestone and grits	none commented	Hudleston (1930)
Feldon Burn	blanket peat	till	Second grit (sandstone)	spring-fed failure associated with base of major sandstone band	Johnson (1992)
Hart Hope	peaty moorland	till	Sandstone and grit	impervious till	Warburton and Higgitt (1998)
Iron Band	blanket peat		Sandstone and grit	unpublished	n/a
Langdon Beck	blanket peat	till	Upper and Middle Carboniferous limestone	unpublished	n/a
Langdon Head	blanket peat	sandy solifluction clay	Upper and Middle Carboniferous limestone	captured flush and pipes	Carling (1986)
Meldon Hill East	blanket peat	solifluction clay with sandstone fragments	Sandstone and shale	sandstone fragments weaken surface boulder clay	Crisp *et al.* (1964)
Meldon Hill West	blanket peat	solifluction clay with sandstone fragments	Sandstone and shale	sandstone fragments weaken surface boulder clay	Crisp *et al.* (1964)
Middlehope	blanket peat	till	Upper and Middle Carboniferous limestone	unpublished	n/a
Nein Head 2	deep peat	blue-grey solifluction clay, locally sandy or containing crusty sandstone pebbles	Upper and Middle Carboniferous limestone	pipes present at peat substrate interface	Carling (1986)
Nein Head 3	fibrous peat	blue-grey solifluction clay	Upper and Middle Carboniferous limestone	pipes present at peat substrate interface	Carling (1986)
West Grain	peat and mineral soil	blue-grey solifluction clay	Upper and Middle Carboniferous limestone	none commented	Carling (1986)

* peat termed blanket peat unless otherwise commented by authors

mass has formed as a result of the impervious substrate, it may also act to modify it physically by loading, and chemically through the interaction of peat water and humic compounds with the clay mineral fraction. Table 2.4 illustrates the geological setting of peat slide sites in the North Pennines, showing the solid geology and overlying drift geology that forms the substrate for the peat failures. All sites share common underlying solid geology of Carboniferous limestones and grits. Draped over this is a layer of glacial till, variously comprised of heavy clay-sandy/clay matrix within which are set large sandstone clasts. There is an assumption of solifluction activity attached to many of the slide locations, though sedimentological evidence for this is rarely described. The peat slides themselves are scattered across the North Pennines, in three distinct clusters. The westernmost group are the Meldon Hill failures. Three have been recorded (Crisp *et al.*, 1964), but only two could reliably be located, Meldon Hill East and West. The southernmost group comprise the Stainmore failures of Iron Band and Dow Crag, the latter documented by Hudleston in 1930. The largest group comprises a spread of failures near Noon Hill in the central North Pennines, spanning 32 years from 1963 to 1995. Scattered examples are found in the far west (Benty Hill and Coldcleugh Head) and north-east (Middlehope and Feldon Burn). These failures are described in greater detail throughout the rest of this thesis. The next section describes how this regional set are set within a global context.

2.5.3 A synthesis of data sources

Given the relatively small number of peat failures distributed globally, an opportunity exists to catalogue all of the known, published examples, and in the process provide a synthesis of form, materials, mechanism and recovery that has hitherto been absent. In this respect, the qualitative review provided previously exceeds any of the prior summaries of peat mass movement. However, a more rigid and robust synthesis may be provided in the form of a database. Databases in geomorphology are relatively rare. This is partly because form-process relationships may prevent simple summaries of spatial and temporal variables. For example, a hydrologist might compile a database dealing with exclusively flow related time series data at a single gauging station, whilst the geomorphologist might record sediment sources, sinks and transfers of different sized sediment along the same reach. Both areas are of relevance to geomorphology, but neither database would be compatible with the other. More usually, summary data is compiled into simple lists or tables and not related to other fields of geomorphological systems.

Landslides, as discrete events with quantifiable morphological components, have given rise to some notable examples of databases. These have often fed G.I.S. driven spatial analyses of landslide hazards across large regions (Mejia-Navarro *et al.,* 1994; Dikau *et al.*,1996; Miller and Sias, 1998). Such approaches examine the spatial distribution of large slide populations with reference to topographic, climatic and geological factors. They rarely include details of morphology, mechanism or materials. The most thorough database, not specifically coupled to a G.I.S. is that of New Zealand (Glade and Crozier, 1996), incorporating geomorphological, geological and socio-economic criteria. Similarly, the Department of the Environment have compiled a UK wide database of relict and active landslides (Jones and Lee, 1994), incorporating geomorphological, geological, morphometric and economic categories. Dikau *et al.* (1996) cite an equivalent European landslide database. The development of landslide scars post-failure, and their influence upon landscape evolution has yet to be considered using databases.

The synthesis provided by the database approach in this thesis has three major aims:

i) to summarise quantitatively the range of morphological, mechanistic and recovery characteristics of all peat mass movement types.

ii) to examine the basis for a two-fold division of peat mass movement types into peat slides and bog bursts.

iii) to highlight inconsistencies and absences of data in the peat mass movement literature published to date.

Figure 1.1 illustrates how this synthesis feeds into hypothesis generation and the empirical aspects of the thesis, described in the following section. Because of the breadth of this study, detailed explanation of methodology and procedures comprise the beginning of each themed chapter, with results and interpretation following. It should be noted at this stage that bog bursts are not considered in detail due to the lack of availability of a regional set.

2.5.4 Peat slide morphology, mechanisms and recovery

In the absence of direct monitoring of peat landslide events, detailed field mapping of morphology has provided the main source of evidence of geomorphological activity (e.g. Mitchell, 1938; Wilson and Hegarty, 1993; Selkirk, 1996; Figure 2.12). This has often been complemented by hillslope transects of the scar and deposit zones (e.g. Praeger, 1897; Carling, 1986; Alexander *et al.*, 1986; Wilson and Hegarty, 1993). Extension of these transects to full hillslope profiles may provide an indication of the topographic setting of each failure. Such quantitative expressions of landscape form are used extensively in geomorphology (Young, 1971; Parsons, 1979; Cox, 1990), and simple summaries of slope geometry have been used in the discussion of a number of peat landslides (Mitchell, 1938; Alexander *et al*, 1986). Both maps and transects will be utilised in the assessment of morphology and topography. In the case of peat mass movements, the dominant failure process is regarded as fairly instantaneous, and it is the distribution of material types (rafts, blocks, slurry) that is indicative of spatial variation in process type and rate across individual sites. The geomorphological maps used in this thesis will be based primarily on demarcation of scar extents, noting of tension features such as scars and cracks, and distribution of the main deposit types. In this respect, they are similar to maps produced by Wilson and Hegarty (1993) for peat slides, and Lewkowicz (1990) for active layer slides.

Geomorphological mapping will be supplemented with detailed recording of morphological units, their dimensions and distribution. This will include full survey of all deposit forms, and features indicative of local stress fields, including cracks, tears and compression ridges. The methods employed are described further in Chapter 4.

The mechanistic behaviour of landslides may be considered in terms of the processes governing their initiation and those governing the movement and deposition of sediment, or runout (Dikau *et al.,* 1996). Initiation and runout will be considered separately. Section 2.3.3. noted the dominance of empirically based slope stability approaches to landslide initiation. In peat slides, there is demonstrated uncertainty over the materials directly involved in the initiation of failure, and further uncertainty in the physical behaviour of peat when subject to stress. Therefore, the methodological approach to material controls on mechanism relates initially to characterising the peat-substrate continuum, and the most likely position of the failure plane. This will be done using a combination of stratigraphic techniques and established bulk material testing procedures, permitting both comparison with the existing peat landslide literature base, and with established methodologies more well practised on landslides in mineral soils. Slope stability approaches will be utilised if there is a material justification for doing so.

In transport and deposition, runout analysis has utilised rheological consideration of debris dynamics, or non-rheological process inference from scar and deposit morphology (e.g. Pierson and Costa, 1987). The peat slurry/block mixtures that appear to characterise peat failures fall outside empirically tested rheological conditions, and attempts to replicate the approaches used in (mineral) sediment water flows would not be empirically based. Non-rheological methods include clast-sedimentology (Krumbein, 1939; Mills, 1983; Van Steijn and Coutard, 1989; Bertran *et al.*, 1997; Major, 1998), interpretation of stratigraphy (Lewkowicz, 1993; Campbell *et al.*, 1995), consideration of mass fluxes using sediment budgets (Reid and Dunne, 1996) and establishment of morphometric relationships on the basis of displaced volumes, relief and transport distances (Bovis and Mears, 1976; Bakkehoi *et al.*, 1983; Cleary and Campbell, 1993; Crozier, 1996). In these cases, provided that landforms have been preserved, processes may be reconstructed many years after the event. A combination of these non-rheological methods will be used in the consideration of peat slide failures, as follows:

i) Characterisation of failure processes through identification of spatial distribution and arrangement of deposit types (rafts, blocks, slurry), and process inference (clast sedimentology approach);

ii) Evaluation of local morpho-topological controls, through quantification of deposit spatial characteristics (morphometric approach);

iii) Quantification of sediment dynamics by construction of event sediment budget (sediment budgeting approach).

The recovery of peat slide scars will utilise an holistic geomorphological, pedological and ecological approach, rarely used in landslide studies (section 2.4). The regional set of peat slide scars in the North Pennines provides a chronosequence of sites with similar underlying geology, climate, relief and peat environment. A geo-ecological approach is employed, which assumes that the degree of recovery is a function of the restorative effects of soil development and revegetation on the one hand, and the degrading effects of geomorphic activity on the other. A sub-sample of the North Pennine failures will be utilised because of the diversity of techniques required to satisfy this approach. Sites will be selected from each of the major spatial clusters described previously, and at the full spectrum of scar ages.

Geomorphological activity is considered through the use of reconstructive sediment budgets. The extent to which sediment export varies with landslide age will provide an indication of the temporally dependent role of geomorphic activity in retarding scar recovery. Revegetation at each slide will be assessed using standard ecological sampling techniques for the evaluation of species variety and extent, including point sampling by quadrat, sampling by transect and vegetation maps. Soil development will also be considered at each failure. Fundamental measures of soil physical, chemical and biological properties will complement vegetation data in the understanding of recovery mechanisms. Assessment of soil structure will be based on particle size and texture. Soil pH and nutrient status will be investigated, and levels of organic matter measured. Ultimately, attempts will be made to identify the sequence of recovery, from initial degradation of the scar surface on exposure, through priming of the substrate for vegetation, and through successional stages that may lead to establishment of a full vegetation cover.

In addition, owing to the limited timescale offered by the North Pennine slide population, a basic modelling approach will be employed based upon the empirical findings of the geo-ecological approach. The Revised Universal Soil Loss Equation (R.U.S.L.E.) has been extensively used to predict sediment losses on the basis of vegetation cover and soil type (Nearing, 1998; Millward and Mersey, 1999; Fox and Bryan, 1999). The reconstructed sediment budgets will be tested against the output of R.U.S.L.E. If good correspondence is found, then R.U.S.L.E. may be used to predict sediment losses for a range of hypothetical slide scar ages, extending beyond that of the available North Pennine set.

2.6. Chapter Summary

Figure 2.16 draws together the methodologies described previously. The significance of peat slides in the landscape may be considered from their global distribution down to micro-scale variations in peat material properties and block characteristics. The methodologies employed at each scale reflect the importance of material, pre-failure landform and wider landscape in governing morphology, mechanism and recovery. Form and process consideration is primarily at the micro and meso-scale, with between-site (local) comparison serving to allow classification, and significance of failure type and extent in regional and global contexts. The research described in the following chapters falls within this framework, the implications of which will be reconsidered in Chapter 9.

This chapter has presented evidence for a two-fold classification of peat mass movements, based on the key features of peat slides and bog bursts. It has described their distribution spatially and through history, and provided literary evidence of their

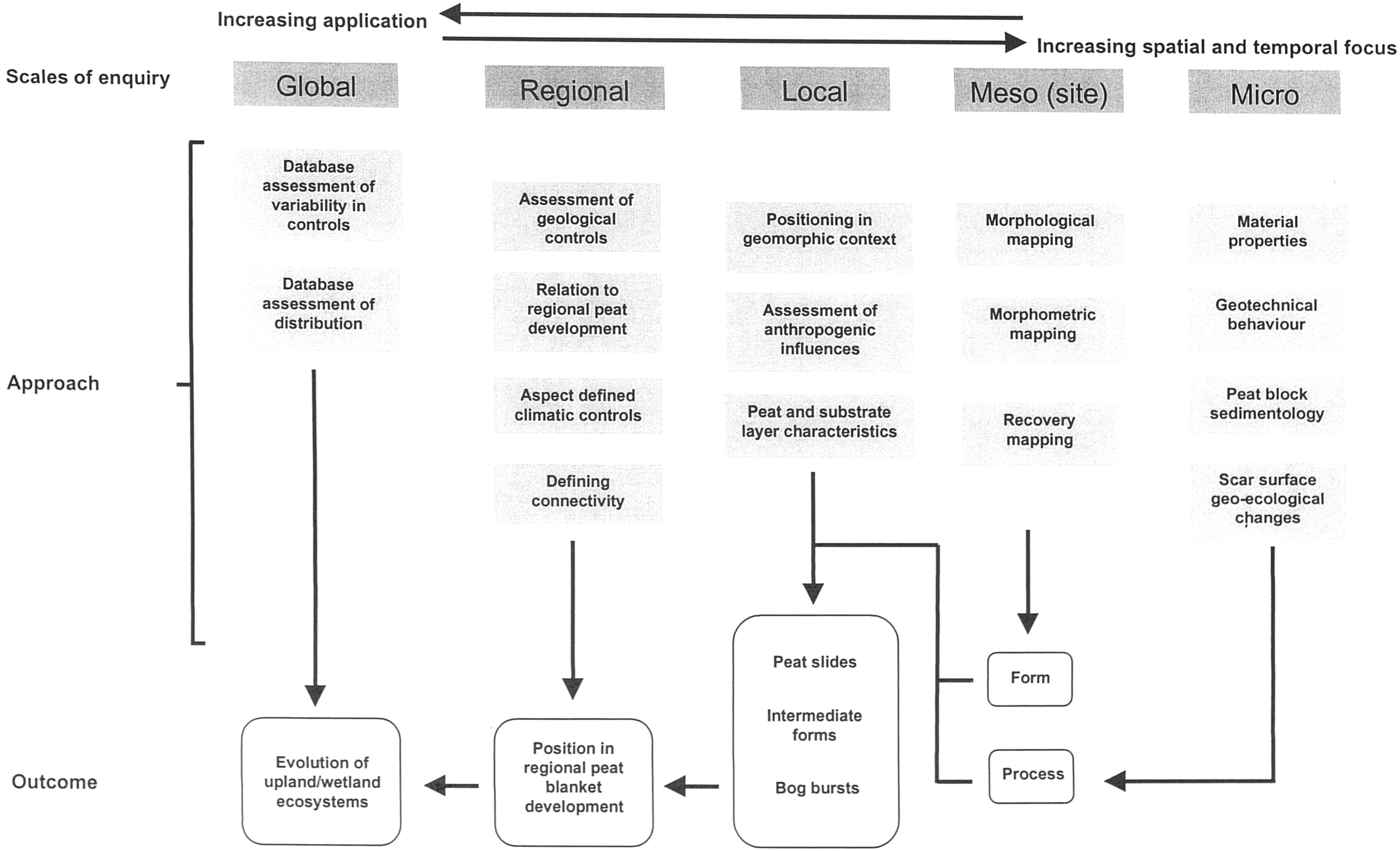


Figure 2.16. Methodological outline showing integration of spatial and temporal components

morphology and suspected failure mechanisms. These ideas have been placed in the context of wider peat blanket themes and assessed relative to mass movement typology in other materials. Their importance as landscape elements has been considered in the light of rate of recovery, and the apparently small total population of failures. While it has been acknowledged that there is a significant awareness of many aspects of peat failures, it has also been demonstrated that a lack of synthesis has prevented the resolution of many key issues. These issues may be divided under the banners of morphology, mechanism and recovery. A methodological approach has been proposed which uses a data-based synthesis to identify gaps in knowledge. These gaps are used subsequently to direct research into the forms, processes and landscape significance of one component of the peat mass movement spectrum, peat slides.

3. THE WORLD PEAT MASS MOVEMENT DATABASE

3.0 Introduction

Peat mass-movements predominantly comprise two failure types, peat slides and bog bursts. However, Chapter 2 highlighted a lack of systematic assessment of these features in the field, and difficulties in separating or relating the two morphologies and formative processes. This issue of definition, widespread in mass movement studies, has led Brunsden (1993) to suggest that there is a notorious academic problem inherent in the variety of available landslide description and classification schemes. In order to resolve this problem for peat landslides, a database has been compiled that draws together essential aspects of peat mass movement compiled from literary and field sources.

The database approaches this data set by adopting the consensus viewpoint discussed in the previous chapter. This assumes that slides and bursts are characterised by differing processes and morphologies. Each database record (or individual failure) is categorised as either a slide or burst according to the criteria for classification discussed in Chapter 2. The subsequent analyses test whether the consensus viewpoint is internally valid for slides and bursts.

This chapter describes the database format, the collection and interpretation of sources, and summary relationships within the contexts of morphology, mechanism and recovery for both peat slides and bog bursts. A synthesis of the information is used to generate hypotheses that form the basis of the empirical research in this thesis.

3.1 Methodology

The main aims of the database approach are fourfold. Firstly, to produce and utilise a framework for data storage, appropriate to the range of data sources from which peat landslide information is available. Secondly, to perform an exploratory analysis of this data with respect to differences and similarities between peat slide and bog burst events. Thirdly, to establish deficiencies in the data sources, in terms of both coverage and interpretation, and finally to investigate whether there is morphological, mechanistic and recovery specific justification for a regional approach applied to peat slides only in the North Pennine study area. The following sections consider data sources, database structure and format, sources of error in database compilation and the quality of the available sources for this study. Analysis of the database is then described and considered in sections 3.2 and 3.3.

3.1.1 Data sources

After an initial survey of available data sources, the database was compiled through the procedure shown on Figure 3.1. Given the range of terminology previously cited (including *peat slide*, *bog burst*, *bog/peat flow*, *cloudburst*, *waterspout*, *peaty-soil flow*, *debacle*, *moorbruchkatastrophie*, *glissement de tourbiere*), an exhaustive literature search was conducted using popular electronic bibliographic search engines (including GEOBASE and B.I.D.S.) under all known terms for peat mass movements. Web-based search engines (for example, GOOGLE) were also used. This produced an initial set of sources, from peer reviewed journal articles through to excerpts from narratives and newspapers.

Electronic and web-based searches were limited by the scope of each search engine. For example, GEOBASE does not at present extend to publications prior to 1980. Extension of the dataset backwards of these limits required searches through all reference lists within the publications already collected. All potential sources identified in this manner were obtained through inter-library loans, visits to local archives (e.g. Alnwick Library for Bloodybush Edge), and the British Library Document Supply Centre. Attendance at conferences was used to publicise the database, and the range of data sources was increased through personal communications with a number of academic and non-academic contacts. Figure 3.2 illustrates the diversity in sources for the database. The process of collation is ongoing, and although analysis is presented here, the database may be considered as a 'work-in-progress'.

Subsequent to the collection of a majority of the data, the quality of the sources was evaluated. The database pro-forma in Figure 3.3 represents the full range of data recorded. The rationale for this structure, and the format of the data are considered in the following section, with data limitations and sources of error discussed.

3.1.2 Database structure and themes

Modern databases comprise two main structural types: hierarchical and relational

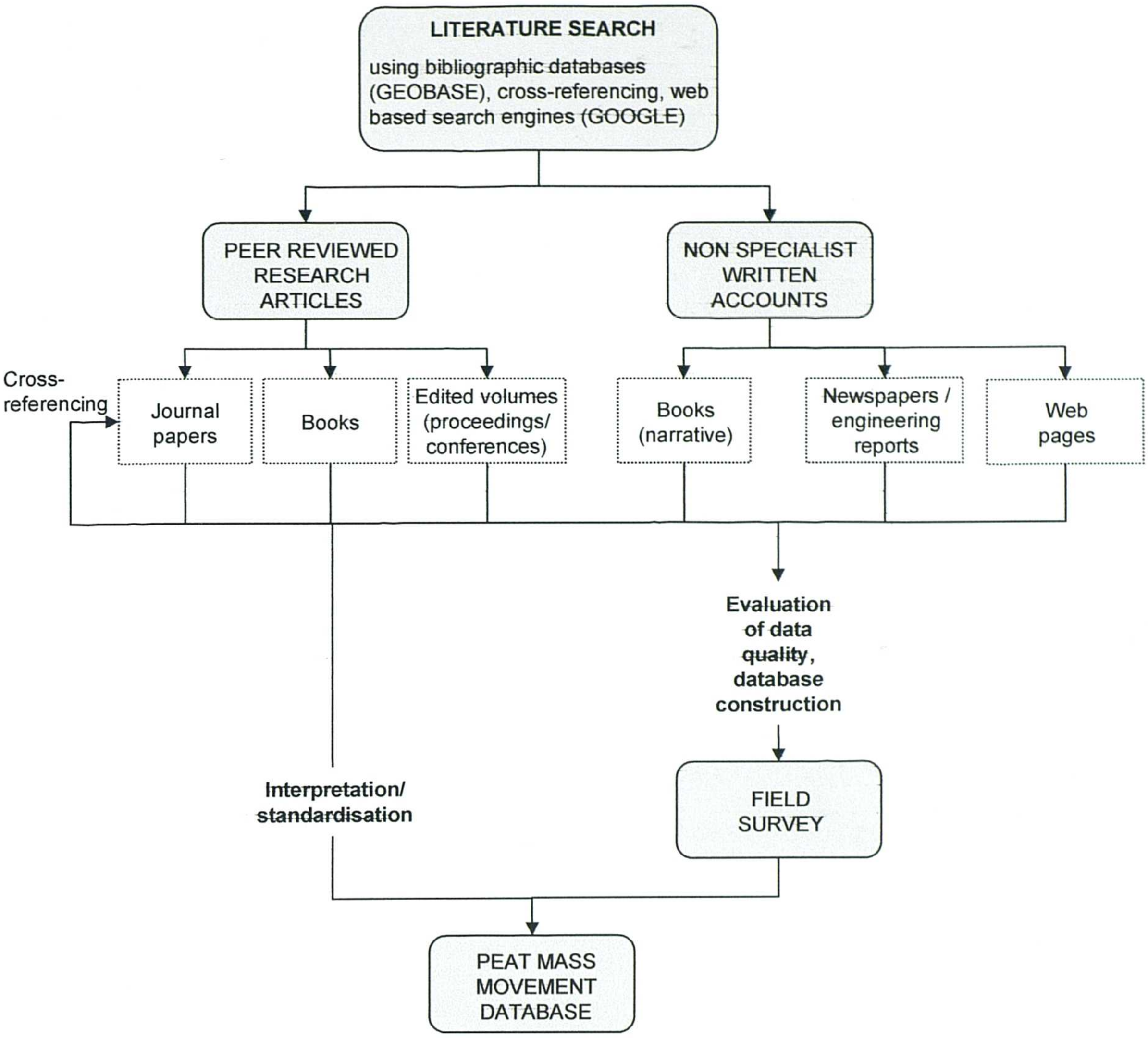


Figure 3.1 Procedure for database construction, from primary sources, through cross-referencing to field validation.

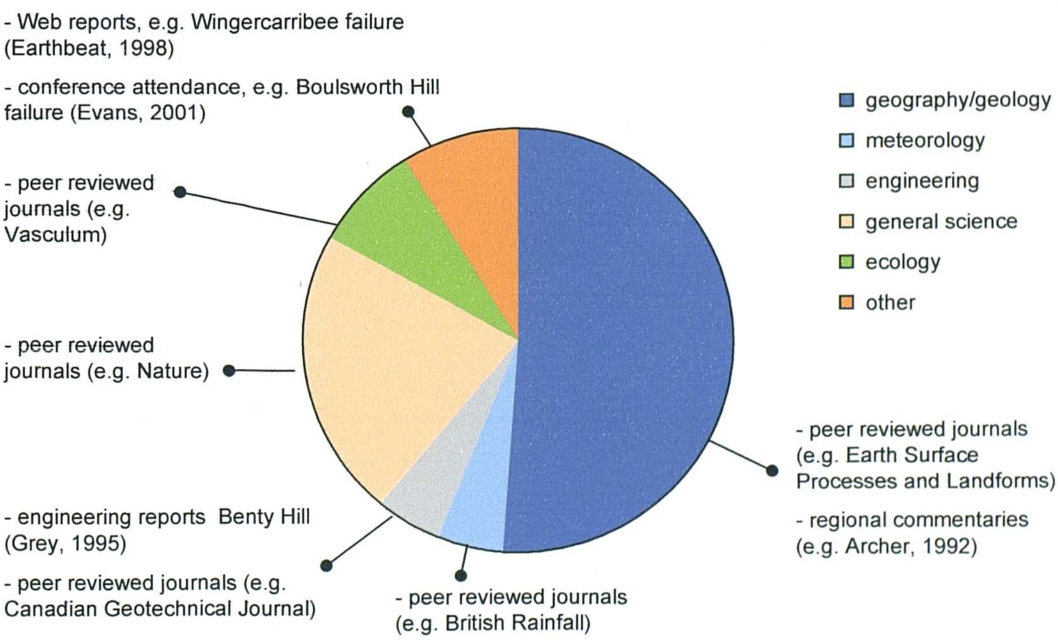


Figure 3.2. Data sources for the peat mass movement database

(Figure 3.4). Hierarchical databases adopt an inverted tree-like structure (Frizado, 1992) linked by parent-daughter relationships, where layers of features may stem from one of the features in the layer above. Relational databases structure data within tables, and are particularly useful in their capacity to interlink (or relate) two or more databases through a common field. For example, in the database structure shown in Figure 3.3, the field 'Blocks' in the 'Morphological characteristics' section contains a sub-database of fields and records relating to blocks (e.g. Figure 3.4b). These include x, y and z-axes and orientation for a set of numbered blocks 1-100. Hence there is a related database comprising 100 records, each described by four fields.

The database described here has been set up as a relational database, comprising 138 records, and 65 fields organised into six major themes. Each record represents a discrete mass movement form, including further subsequent movements at that specific location. Themed sections refer to distinct analytical themes applicable to peat mass movements, and reviewed in the previous chapter. The 'drainage setting' and 'material characteristics' sections consider site controls on initiation and mechanism. The 'morphology' and 'morphometry' themes consider form and dimensional characteristics. The 'post-failure development' section considers aspects of recovery and continuing site degradation. This structure permits the addition of further sub-databases in the future, for example, the addition of temporally separate recovery studies undertaken at specific sites over longer time periods.

Figure 3.3 illustrates a blank database sheet. Where a class is ascribed to a feature, all available options are listed (e.g. displacement - minor/major/complete); where numeric data are required, units and decimal places (as an example) are displayed; where a statement of presence or absence is needed Y/N (for Yes/No) is shown; and where a variable is flexibly represented by text, 'string' is noted. A glossary of terms, and explanations of each possible field entry is listed in Appendix 1.

3.1.2.1 General description

The general description section provides a context for each event listed in the database. The 'reference' section indicates the primary source of information about the failure, sufficient in detail to allow the reference to be traced from the database entry alone. Where the reference details are listed 'not defined', no published reference has been located for the event, and this thesis acts as the main source of data, be it primary (field surveyed) or secondary (information relayed to this author by somebody

SLIDE NAME "string"

GENERAL DESCRIPTIONS

Reference

Author/s	" string "
Title	" string "
Publication	" string "
Publication Date	" year "
Publisher	" string "

Context

Date of failure	" day/month/year "
Terminology	" slide/burst/slump "
Activity	" discrete/multiple/cyclic "
Blanket location	" margin/to-margin/within "
Location	" string "
Country	" string "
Grid reference	" sheet/6 figure grid ref. "

MORPHOLOGICAL CHARACTERISTICS

Basic

Blocks	" Y/N "
Rafts	" Y/N "
Slurry	" Y/N "
Max. block size	" a-axis x b-axis x c-axis "(m)
Distribution	" within/beyond/to-channel "
Displacement	" minor/major/complete "

Tension cracks	" Y/N "
Tears	" Y/N "
Post-failure tc/te	" Y/N "
Max crack depth	" depth " (m)

Levees/block-lines	" Y/N "

DRAINAGE SETTING

Pipes	" Y/N "
Max pipe diam.	" pipe diameter " (m)
Density	" discrete/multiple "

Gripping/cutting	" Y/N "
Max. drain dim.	" pipe width/pipe depth " (m)
Location	" head/margin/head+margin "

Drainage location	" above/within/beneath/margin"
Slope/chan coupl.	" Y/N "

MORPHOMETRY

Basic

Aspect		" *** " (degrees)
Altitude		" *** " (metres)
Length:	scar	" *** " (metres)
	disturbance	" *** " (metres)
	deposit	" *** " (metres)
	excavated	" *** " (metres)
Width:	scar	" ** " (metres)
	deposit	" ** " (metres)
Depth	scar	" *.* " (metres)
	deposit	" *.* " (metres)
Slope angle:	upper	" **.* " (degrees)
	lower	" **.* " (degrees)
Slope form		" convex/concave/rectilinear "
Volume		" ***** " (m^3)

MATERIAL CHARACTERISTICS

Bulk density		" *.** " (t m^{-3})
Moisture content		" *** " (%)
Strength	Cohesion	" **.** " (kN m^{-2})
	A.O.I.F.	" **.** " (degrees)

Stratigraphy:	Acrotelm	" string "
	Catotelm	" string "
	Basal	" string "
	Substrate	" string "

Failure plane:	" above/at interface/below "

POST FAILURE DEVELOPMENT

Recovery

Duration	" *** " (years)
Soil development	" Y/N "
Ponding	" Y/N "
Peat Restabilisation	" Y/N "

Revegetation:

Dom spp 1	*" string "*
Dom spp 2	*" string "*
Dom spp 3	*" string "*

Degradation

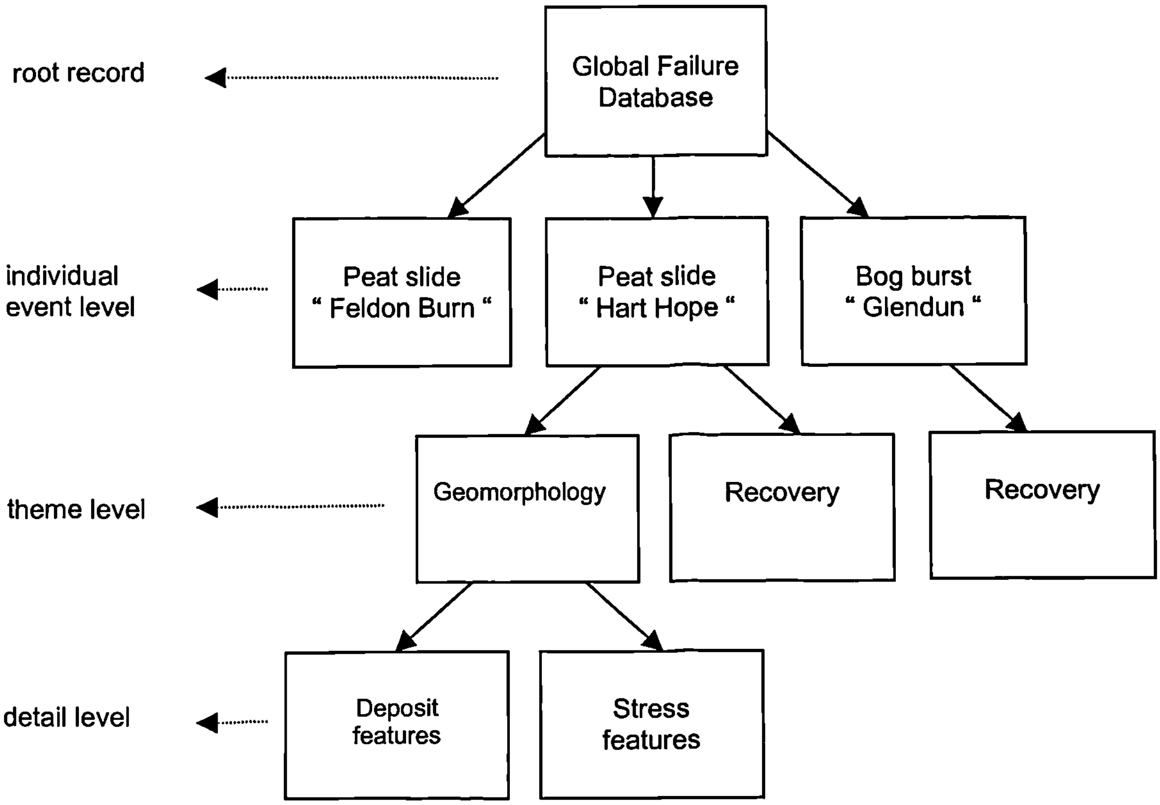
Drainage/dissection	" Y/N "
Grazing	" Y/N "
Burning	" Y/N "
Secondary failures	" Y/N "

NB: Note 'not defined' where field contents unknown

Figure 3.3. Example database pro-forma

Figure 3.4. Example of hierarchical and relational database structures for peat mass movements (after Frizado, 1992)

a) Hierarchical: database sections are linked by "parent-daughter" relationships



b) Relational: three databases are linked by fields in the main database

Slide name	Year	Author	Blocks	Cracks
Feldon Burn	1992	Johnson	Y	Y
Hart Hope	1995	Warburton	Y	Y
Glendun	1964	Colhoun	Y	N
Skerry Hill	1981	Wilson	N	N
Iron Band	1963	Hudleston	N	Y
Dougal	1999	Mills	Y	N
Dales Voe I	1976	Veyret	N	N

Block	x (m)	y (m)	z (m)	Aspect
1	5.4	4.3	0.8	354
2	4.3	3.1	0.6	123
3	5.7	4.8	0.9	324
4	2.3	1.8	1.2	311
5	3.6	2.9	1.0	245

Author	Journal
Johnson	Vasculum v76(4)
Warburton	Geomorphological Studies in the North Pennines - Field Guide
Colhoun	Sci Proc RDS, Series A (2), pp 163-174
Wilson	ESP&L, Vol18
Hudleston	British Rainfall 1930
Mills	n/a
Veyret	Norois, v40, n160, pp 653-664

else). This level of detail allows reliability of the data sources to be assessed, and reveals the academic or non-academic discipline in which the event is considered. For example, failures considered within the engineering literature may contain a greater coverage of materials information, and those within the ecological literature a greater depth of recovery data.

The 'context' section provides a spatial and temporal setting for each event. Failures may be located spatially through their grid reference (where supplied or available through field survey), location in the peat blanket (see Figure 3.5), regional location (by administrative region in the UK and Ireland, and geographically elsewhere) and country. A temporal setting is provided by indication of the date of failure (to nearest day) where known, and by an indication of the longer term stability of the failure (discrete, cyclic, multiple).

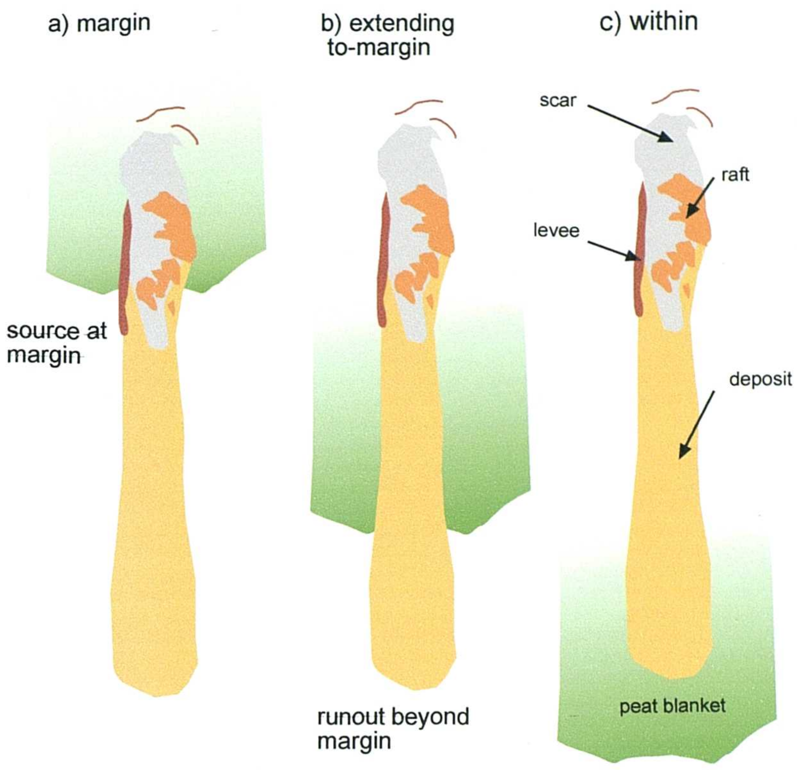
3.1.2.2 Drainage setting

This section considers drainage factors that may contribute to initiation of failure, both natural and artificial. Only discrete linear features, easily assessed in the field or from maps or aerial photographs are considered. Features include soil pipes (which are frequently revealed in peat and substrate faces at scar margins), grips or moor drains, and natural subaerial drainage networks such as streams or gullies. Much of the original drainage system may have been removed by peat transport, and hence the location of subaerial drainage is referenced to the scar location (Figure 3.6a and b). If the slope-sediment system (in terms of deposit and subsequent reworked scar material) has become coupled to the local subaerial drainage network, this is noted under 'slope/channel coupling'.

Subsurface drainage (Figure 3.7a) is recorded by absence or presence, and spatially as discrete or multiple. Maximum cross-sectional dimensions are also noted in order to provide an indication of maximum discharge. Channels are recorded with reference to the scar location. Maximum cross-sectional dimensions are recorded for gullies and channels.

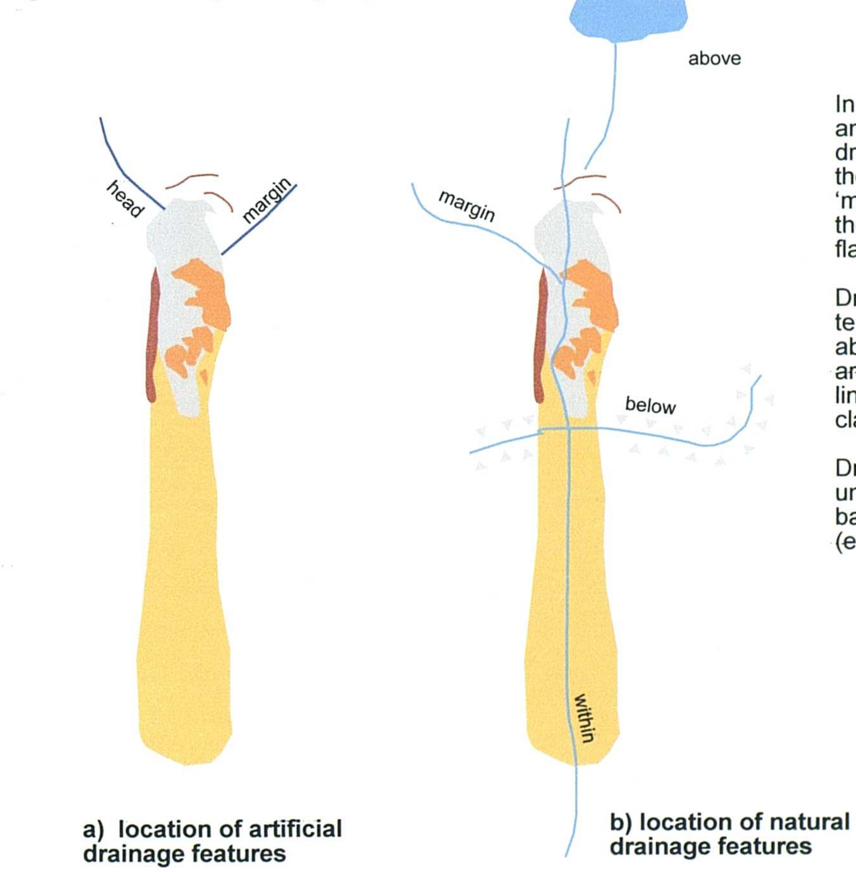
Moor drains, or grips intruding on the scar margin (Figure 3.7c) are recorded by presence or absence, and in maximum dimensions. The location of the grips are considered as inputs of water into the intact peat areas, at the scar head, or into its margins. Both locations may have significance as hydrological controls on initiation,

Figure 3.5. Blanket setting for peat failures



Failures are classified 'within' where all deposit remains within the geographical limits of the peat blanket; 'to-margin' where deposit impinges or passes over the blanket margin; and 'margin' where failure incorporates the margin edge.

Figure 3.6. Drainage setting of peat failures



In the case of both natural and artificial drainage, 'head' drainage feeds directly into the upslope scar margin, and 'margin'drainage feeds into the scar flanks (not deposit flanks).

Drainage 'above' may terminate within the slide or above it, but if the entire scar area contains the drainage line, 'within' is used as the classification.

Drainage 'below' may undercut across the scar base, or drain the scar foot (e.g. a gully head).

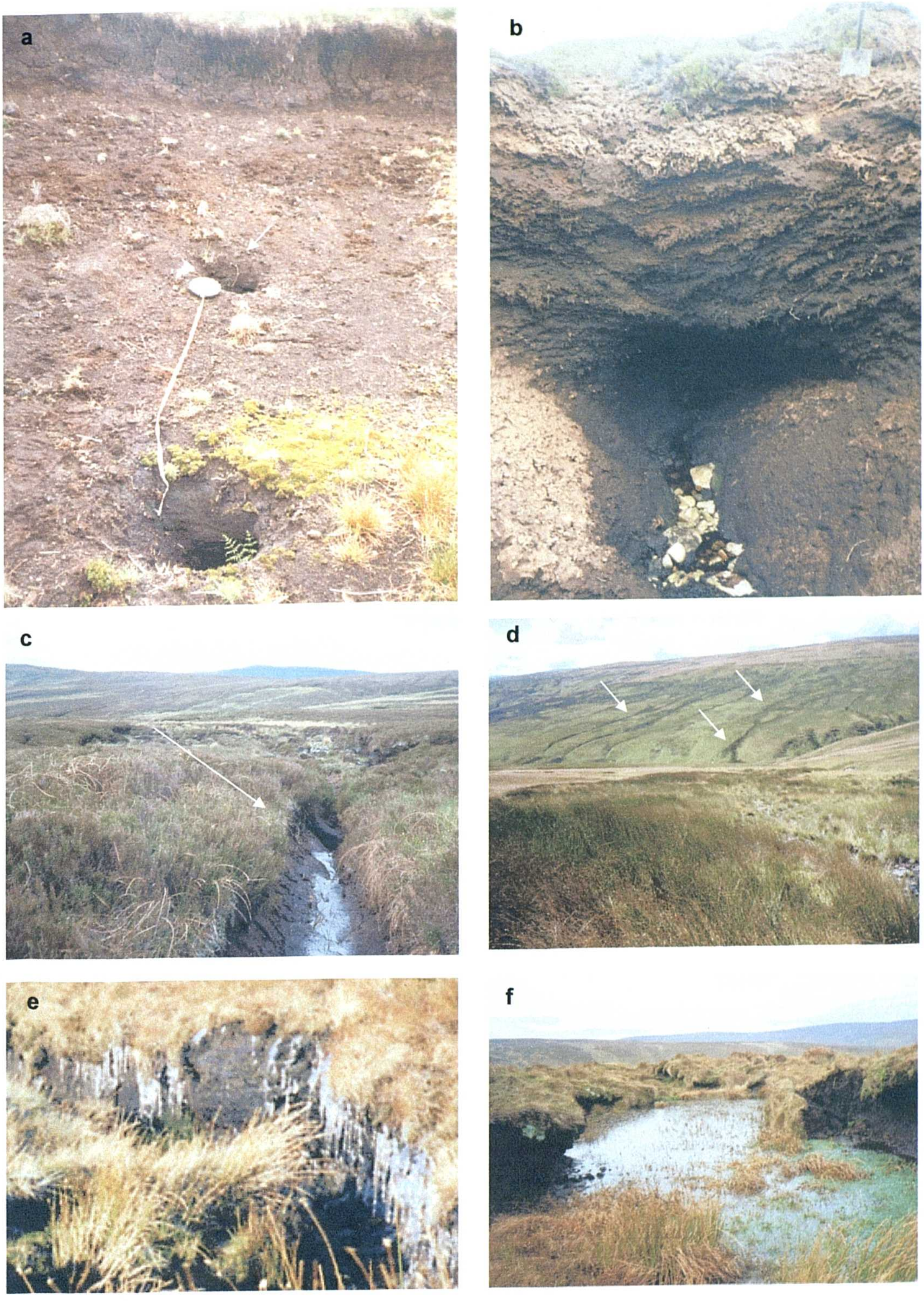


Figure 3.7. Drainage features associated with peat slides and bog bursts. a) karstic pipe network revealed in lower excavated part of Glendun bog burst; b) large pipe, (note spade for scale) in deep peat on Meldon Hill; c) grip feeding the head of Beagh's Head (Co.Antrim) bog burst; d) linear flushes feeding valley side gully network on slope opposite Middlehope peat slide (foreground); e) icicles indicating extent of former acrotelm surface flow at Langdon Head peat slide; f) ponding and vegetation development between raft-jam at Nein Head 2 peat slide.

while grips entering the scar margin may have acted as lines of structural weakness in the former peat surface. In a similar vein, the location of linear cuts (used in peat extraction) are also noted. Drainage features typically found in the vicinity of peat failure scars are shown on Figure 3.7.

3.1.2.3 Morphological characteristics

This section considers the key diagnostic features of bursts and slides. Photographs of the features can be found in Chapter 2. The presence of deposit is noted as either blocks or rafts. There is some ambiguity within the literature as to the criteria for such a division, though designation appears to be a function of size. The database records the presence or absence of rafts and blocks, under the assumption that there is some morphological difference, or implied process control on their formation. The dimensions of the largest deposit mass, be it block or raft, are often reported in the literature, and are also recorded in the database. Subsequent analyses within this chapter investigate a size-basis for a block/raft division of deposit. The absence of either form of deposit would imply complete wastage with time, with long run-out distances, or through rapid remoulding of material during transport. Their distribution may provide information about initial failure conditions (such as water content) and velocity of movement.

The deposit patterns are considered as either block-lines or levees. These may be significant in terms of mode of debris movement, with lateral levees produced by the lateral expulsion of coarser debris behind a leading snout of material. Block-lines may be a product of the breakdown of elongate displaced peat masses. Mode of transport is considered further in Chapter 5.

The presence of slurry is also recorded. This is reported in the literature using a number of terms including 'slurried peat', 'liquefied peat', a 'peat and water mixture', and 'peaty mud'. The absence of any attempts thus far to describe the slurried deposit permits the use of the umbrella term 'slurry' in this context.

The presence or absence of tension features (cracks and tears) is also recorded. Cracks and tears may be intermittent and highly variable in surface dimensions, hence only maximum depth is considered. When compared with peat depth, this data may provide information about the extent to which cracks act as lines of weakness in the peat mass.

3.1.2.4 Morphometry

Scar and deposit dimensions and topographic setting are considered within the 'morphometry' section of the database. The aspect of the downslope axis of the main scar or disturbance area is recorded as a bearing, and the altitude of the highest point (usually the headscar face) is recorded to the nearest 10 m. Both of these variables may be of relevance in terms of climatic controls on failure. For example, aspect is frequently important in determining susceptibility to prevailing climatic conditions, such as heavy rainstorms or rates of snowmelt, while altitude may also be related to climatic conditions, as well as blanket location.

Upper and lower slope angles are recorded around the largest break of slope within the confines of the scar area. If the scar is rectilinear, an equal slope value is entered for both the upper and lower slope angle fields. Both convexities and concavities have been noted for bursts and slides, and as the previous chapter indicated, slope form has been implicated in failure initiation. Slope form is also noted as a separate category. Slope angle often goes unreported within some of the earlier literature sources, but slope form is mentioned.

The maximum dimensions of scar and deposit are considered for all failures. Figure 3.8 represents each morphometric field diagrammatically, using terminology defined by Crozier (1973) for a morphometric derivation of process types. Morphometric indices derived from these dimensions may be related to flow type and behaviour (Crozier, 1973; Cooke and Doornkamp, 1974; East 1978). Four sets of dimensional data are considered. The scar area is defined as the total area over which material has been dislocated and transported, and is represented in terms of maximum length (Lc) and width (Wc). The deposit area (Lm and Wx) represents the areal extent of deposited material, from the furthest upslope point of deposition to the furthest downslope point. These two measures permit assessment of the degree of extension of deposit once movement has initiated, and the degree of lateral spreading. The disturbance length (L) represents the total length of land surface affected by the event, the upslope limit of which is usually the scar head, but may extend further upslope in the form of upslope tears and cracks. The downslope limit of the disturbance area is defined by the furthest downslope extent of uncoupled deposit. Coupled deposits are not considered, because they are difficult to assess, and could theoretically involve disturbance lengths (or distances) of several kilometres. Finally, the excavated length (Lr) refers to the total length of scar free of deposit from the furthest upslope extent of the scar (usually headscar). Excavated length is expected to be small in bog bursts and large in peat

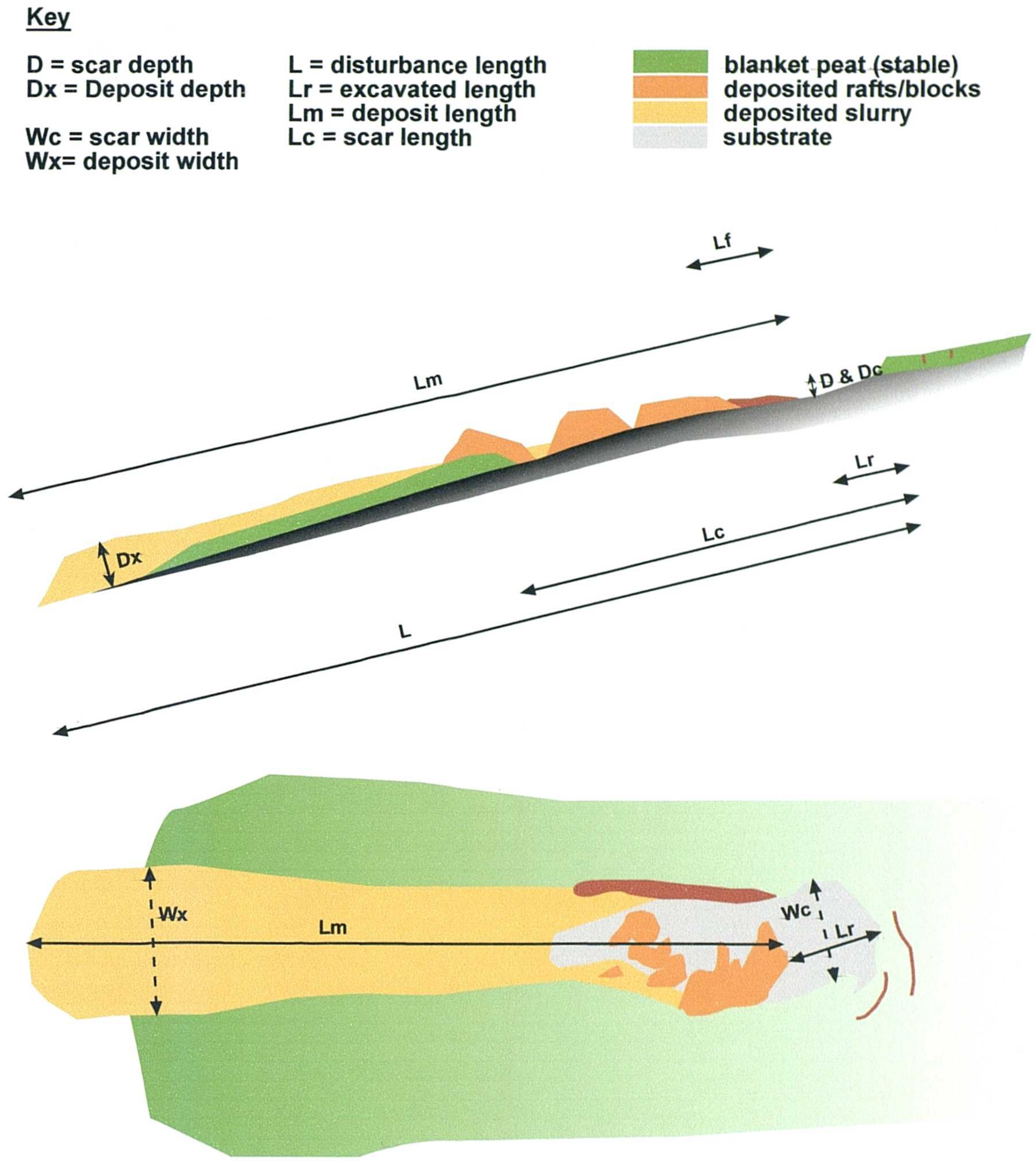


Figure 3.8. Crozier's morphometric indices as applied to peat slides.

slides because of differences in degree of transport. Disturbance length is expected to be greatest in failures on steep slopes, or in particularly wet peat, which may be less viscous and more prone to extension.

Displaced volume is calculated as a product of scar length, width and maximum depth (D). This will tend to overpredict displaced volumes in the case of the more ovoid or irregular scar shapes with very variable peat depths. However, maximum dimensions are frequently the only reported values at failure sites, and this approach is justified in an attempt to be consistent across the whole event population. Maximum deposit depth (Dx) is recorded as the greatest depth of a discrete deposit element. This may be significant where it exceeds scar maximum depth, in illustrating doming of the peat mass within the former intact area.

3.1.2.5 Material characteristics

Material characteristics are considered in terms of general physical properties. Bulk density and field moisture content are the most frequently cited quantitative measures of physical characteristics at failure sites. They provide an indication of consolidation of peat and substrate (where recorded) and the degree of saturation, the latter explicitly implicated in preparation of the slope for failure by a number of authors. The shear strength parameters of cohesion (c) and angle of internal friction (ϕ) are reference indicators of material strength, and as such provide a basis for comparison between failures where the information is available. All data is expressed as S.I. units, a format which frequently requires conversion from older Imperial-based publications.

Stratigraphy is of exposed peat faces at scar margins. A full stratigraphic profile would encompass consideration of fibre thickness and quantity, degree of humification, layer thickness and boundary strength between layers. This is rarely adhered to in the published literature. Instead, qualitative terms such as ‘fibrous’, ‘humified’, ‘cheesy’, ‘greasy’ and ‘amorphous’ are employed in various combinations to describe distinct layers identified in profile. The term ‘fibrous’ has connotations of tensile strength, while ‘amorphous’ suggests an absence of coherent structure. ‘Humified’ may represent an intermediate between the two, with a combination of fibrous and amorphous material. These terms have also been partly quantified in some of the peat geotechnical research (e.g. Landva and Pheeney, 1980) and are employed in this database.

The peat mass is subdivided by hydrological function into acrotelm (surface) and catotelm (permanently waterlogged), with 'fibrous', 'humified' and 'amorphous' used to describe them. Combinations of the three terms are employed. For example, a predominantly fibrous layer is referred to as 'fibrous', while a layer verging on structureless is referred to as 'humified/amorphous'. The material layer immediately above the failure plane is referred to as the basal layer, while the material below the failure plane is termed substrate. If either layer is peat, the terms described previously are used. Otherwise, combinations of 'clay', 'sand', 'clastic' and 'bedrock' are used to describe the nature of the predominantly mineral material.

In addition, the position of the failure plane in relation to the peat-substrate contact is recorded. It may be designated as either 'above' the interface (i.e. within the peat), 'at interface' (i.e. at the contact between the peat and substrate) or 'below' (namely within the substrate). If the failure plane is unknown, the field is completed as 'undefined'.

3.1.2.6 Post failure development

The final theme reflects the development of the scar area subsequent to failure. This is rarely considered in the peat landslide literature (section 2.4), but all fields may be validly completed at any stage after failure.

Fields are separated according to those reflecting increasing landscape stability, or recovery, and those reflecting continuing degradation of the former peat covered surface. A timeframe is provided in the 'time elapsed' field, representing the time elapsed between the failure event and the compilation of recovery/degrading characteristics. In the case of field-surveyed examples in this thesis, the value corresponds to the time since failure to the year 2000. In the case of literature derived sources, it represents time from failure to time of published survey.

Soil development refers to the presence or absence of a soil cover over the former substrate. Essentially, this involves any pedogenic departure from immediately post-failure conditions. Ponding (Figure 3.7d) refers to the development of surface water bodies. These may encourage peat formation through provision of waterlogged conditions, as well as the development of waterborne vegetative species. Peat stabilisation refers to the revegetation and stabilisation of peat 'floes' (scar surface deposits). The presence of these isolated peat bodies within scar areas may represent loci for the growth of peat forming species in the aftermath of failure. Where revegetation has occurred, the three dominant species (by areal coverage) are recorded.

Scar degradation is considered in the presence or absence of drainage development. This may be any combination of rilling, gully erosion or headcut channel migration. In practice, all three of these processes may operate, and at present, there is little or no information available at sites other than those surveyed within this thesis. Hence, only the presence or absence of erosion is noted. Evidence of grazing is identified by animal droppings, chewed vegetation or rubbings of fleece at scar margins. Grazing may impede recovery by preventing the development of stabilising vegetation. Equally, compaction of the scar surface by trampling may make it more susceptible to erosion. If burning has taken place, this is also noted, with its obvious implications for vegetation loss. Finally, secondary failures are noted, both as slumping and toppling of scar margins, and reactivation of unstable sections of the peat mass adjoining the existing scar.

3.1.3 Data quality and sources of error

There are three main limitations to the database: the availability of primary and secondary sources; the accuracy of sources; and the interpretation of sources. The database represents extensive searching and cross-referencing of journal articles, book reports, eye-witness accounts, and field and aerial photograph reconnaissance. However, it is quite possible that there are un-referenced reports of peat landslides that have not been located. It is unlikely that such omission would represent a significant number of new failures relative to those already considered in the database. Of the academic literature, approximately 40% of records are primary reports of individual or groups of peat failures. A further 45% are secondary sources, collating miscellaneous reports into summary format. Some 15% are tertiary sources, and may be unreliable. The academic literature provides around 95% of the total population of failures. The remaining sources are primarily based upon personal communications or direct field survey.

The accuracy of the data sources is open to question, as different publications have different contexts for investigation of peat failure sites. For example, ecologists may misinterpret geomorphological forms, while geomorphologists confuse plant species in the assessment of recovery. The most significant problem with the earliest approaches is a tendency to perhaps over-estimate the magnitude of the events. These issues are best summarised by McEwen and Withers (1989), who use the example of the Solway

Moss burst in Scotland, 1771, to assess the accuracy of historical newspaper and literature accounts. The first report of the failure, originating in the 18th century, was written in the absence of current geomorphological theory. A similar contemporary account, with a history of case studies with which to compare, might have been quite different. The destruction of the Solway feature by subsequent human activity prevented a re-examination of the site .

The final potential source of error lies with the interpretation of sources for entry into the database. In order to avoid potential pitfalls, the database has been designed in a way that attempts to avoid 'interpretation' of process or form. For example, 'fibrous' material properties are not recorded as evidence of 'tensile strength'. Equally, subjective assessments of unobserved process rates are not considered. For example, some authors present estimates of total duration of the event, and even debris velocities. These are not usually based upon direct observation, nor on rheological reconstruction, and are thus disregarded.

Deposition and tension features, dimensions and peat material properties are all factors which are clear in definition, and may be visible on aerial photographs, maps or within published field logs. In this database, the presence or absence of key diagnostic features is used where possible, as this is the most consistently applicable approach across sources. Maximum dimensions are specified for morphometric analyses, as maximum dimensions are more frequently noted than mean dimensions.

3.2 Results

The previous chapter provided a qualitative overview of the peat mass movement literature, focusing in particular on mechanisms of failure and observations of morphology. This chapter undertakes the first quantitative analysis of available evidence, using the database. The approach described here is exploratory, and analysis is organised under five main themes. The first section considers the nature and quality of the data sources, and refers mainly to information within the 'General description' theme. The second describes the spatio-temporal context of the landslide population, derived from contextual information stored under the same theme. The remaining three sections consider database variables under the banners of morphology, mechanism and recovery. Morphological units and dimensions of landslide form are derived from the 'morphology' and 'morphometry' sections. Factors influential in initiation and transport are derived from the 'drainage setting' and 'material characteristics' sections. Factors promoting or impeding the recovery of the landslide sites are derived from the 'post-failure development' section.

3.2.1 The nature and quality of the dataset

The database currently consists of 138 discrete peat failures. Table 3.1 shows the percentage of failures for which more than 50% of each themed section has completed fields. 79 of the failures are classified as peat slides, 49 as bog bursts, 6 as slumps and 4 are unclassified or unclassifiable. Slumps and unclassified features are excluded from subsequent analysis, as the sub-populations are too small to analyse independently, and because they do not contribute to the wider discussion of slide and burst morphology and process.

	Percentage of themed sections > 50% complete		
	Slides	Bursts	Slumps
Context	98.7	89.8	50.0
Drainage setting	36.7	28.6	33.3
Morphology	77.2	61.2	83.3
Morphometry	89.9	67.3	83.3
Material characteristics	64.6	61.2	83.3
Post-failure development	44.3	32.7	16.7
Total number of failures	**79**	**49**	**6**

Table 3.1. Available of information by database theme

In terms of data sources, the largest proportion of failures have been recorded in geographical or geological literature (49%). This is unsurprising given both the wide range of publications that this encompasses and the traditions of landslide study in these disciplines. General science publications (usually books) provide around 20% of the examples, and ecological studies around 9%. Engineering literature supplies few examples (less than 3%), and this is surprising given the importance of engineering in slope stability studies. Taken with 'other' sources (12%) which includes field survey by this author, a 'geographical' approach has been adopted for up to 61% of the total number of failure sites.

Although there are 138 discrete failures, the literature summarising them is somewhat smaller. For example, there are three compendia which represent 26% of the individual events, two of which are secondary sources compiling miscellaneous newspaper reports that are no longer available (Sollas *et al.*, 1897 and Feehan and Donovan, 1996). 25% are reported as small clusters of between five and nine failures. Another 17.5% are considered as pairs or trios of failures, often multiple and occurring at the same time. The remaining 31.5% are reported as discrete event case studies. It is this last set that provide the fullest accounts of the peat failure population, and for which data availability is greatest.

Given the variety of sources, data availability is as expected, quite variable. Table 3.1 indicates that, generally speaking, there is more information available for peat slides than bog bursts, with a greater proportion of the former having more than 50% of database fields completed. In both cases, information is least available with respect to drainage setting (28-36%) and post-failure development (32-44%). Morphometry and morphology information is well supplied for both slides (77-89%) and bursts (61-67%), and this probably relates to the essentially geographical (and often geomorphological) nature of the greater body of source literature. Material characteristics are considered at a reasonably large number of sites (61-64%) given that engineering characteristics of materials fall outside the scope of most of the literature base.

3.2.2 Spatial and temporal context for peat failures

The geographical distribution of peat mass-movements was examined in detail in the previous chapter (sections 2.1.2). However, the detailed setting of these failures has yet to be discussed, in particular their location in the blanket peat system as a whole, and their hillslope topographic settings. It is very rare that the precise blanket location is discussed in reports, but references to blanket margins and maps of failure sites frequently provide information about their impact. Failures whose deposits do not travel beyond the peat blanket margin essentially represent adjustments within the peat blanket system, rather than an impact on adjacent landscape systems.

Approximately 55% of recorded bog bursts never impact directly on systems outside the peat blanket, 21.4% occur as marginal outbursts, and 15% discharge their deposits over the margin edge. A far greater proportion of slides occur at the blanket edge (35.9%), with a further 24.4% running out over the blanket margin. 38.5% occur entirely with the limits of the peat blanket. This may reflect the importance of greater slope angles associated with slides at margin edges, and this idea is considered shortly. The proximity of many slides to blanket margins and blanket peripheral drainage networks is supported by the 56% that are recorded as slope-channel coupled. The percentage of coupled bursts is similarly high, at 61%. While many of the latter failures may not impact directly on blanket external systems, their deposits may find their way onto valley floors through the connectivity of the regional drainage network. Such impacts frequently form the basis of reports of bog burst events.

The spatial location of failures may be considered in terms of their clustering (Table 3.2). 67% of peat slides occur on the same hillslopes as other peat failures. These may be as sets of multiple failures, such as the Noon Hill peat slides (Carling, 1986), or as individual failures occurring on the same slope but on different occasions, such as the Skerry Hill failures (Wilson and Hegarty, 1993). Distances between failures may range between a few tens of metres up to several hundred metres. There is insufficient published information to quantify these distances. 28% of the bog burst population occur near to other bog bursts. Despite the number of spatially clustered examples, there are no cases of bog bursts occurring on the same hillslopes as peat slides.

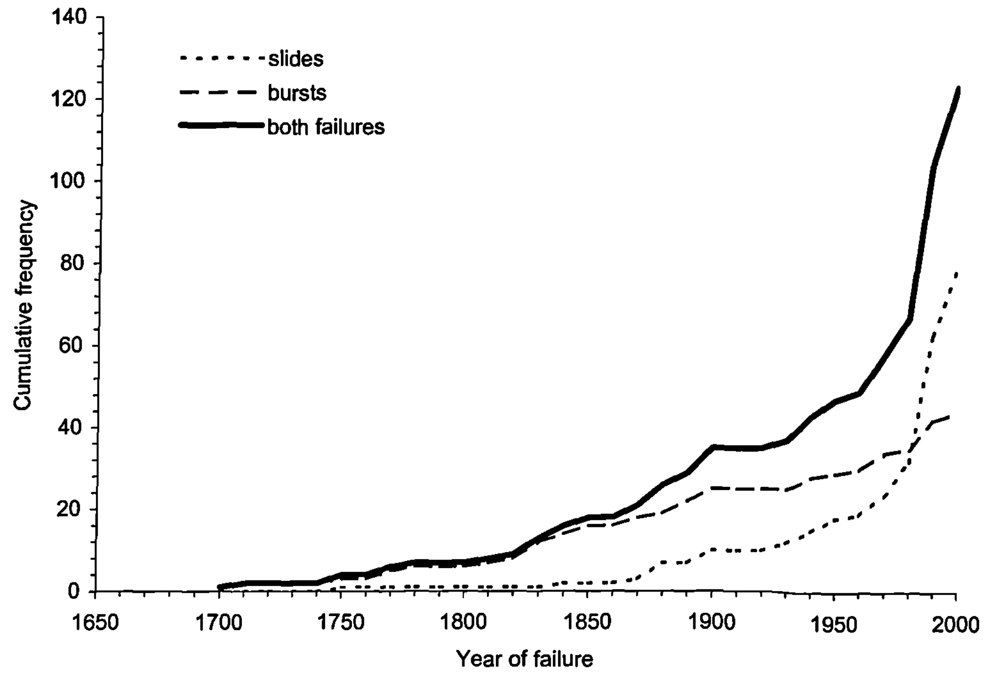
Table 3.2 also shows the number of slides and bursts that occur on the same date (and it is assumed under the same driving climatic conditions). Nearly 70% of the slides on record occur in association with other slides, for example, those at Hermitage Water (Acreman, 1991) and five of the North Pennine failures. A majority of recorded bog bursts occur in isolation. 31.1% of peat slides have been reported in close proximity to one another (same slope/hillside) and at the same time (hence 'multiple'), while the same can only be said of 13% of bursts. Nearly all the remaining events have occurred in proximity to one another but at different times, or as discrete failures in space and time. Very few events re-mobilise at a later date and can be regarded as 'cyclic' (4% of slides, no bursts). The tendency of slides to cluster, relative to bursts cannot be explained at this stage.

Figure 3.9 shows a decadal plot of cumulative frequency of slides and bursts, considered separately, and together. Data is grouped by decade. For example, all failures occurring between 1691 and 1700 are plotted at 1700. Reports of bog bursts continue steadily from their onset in the 1690s to the present day. Peat slides are first reported in the 1740s, and are recorded at a similar rate to bog bursts until the early 1960s. Thereafter, there is a rapid and continuing increase in the number of events. The total number of peat slides reported overtakes the number of bog bursts from the 1980s, with a spate of clustered failures. The continuity of reports over the last three centuries suggest that there has been an awareness of peat failures as landscape features for some time. However, the rapid increase in peat slide numbers may

Table 3.2. Spatial and temporal clustering of peat slides and bog bursts

	Temporal context					Spatial context	
	Clustered	Non-clustered	Cyclic	Multiple	Discrete	Clustered	Non-clustered
Peat slides	69.6	30.4	4.1	17.5	78.4	67.0	33.0
Bog bursts	28.3	71.7	0.0	13.0	87.0	28.0	72.0

Figure 3.9. Peat failure cumulative frequency by decade



suggest a real increase in frequency, rather than just an increase in awareness of them. Finer temporal resolution is available where failures are considered seasonally and by month of occurrence. This is examined further in section 3.2.4.

3.2.3 Slide and burst morphology

Landforms at peat failures may be considered in terms of morphological units (e.g. blocks), and in terms of landform dimension or morphometry. This section begins with a consideration of the key morphological units, rafts and blocks (solid deposit), slurry, cracks, tears and composite deposit features (block-lines and levees). Scar and deposit dimensions are then considered within the framework outlined in section 3.1.2.4. Subsequently, these scar and deposit dimensions are related to the type and magnitude of morphological unit at slides and bursts. Finally, Crozier's (1973) morphometric classification is applied to the slide and burst sites for comparison with non-peat failures. Crozier infers process from the degree of extension and lateral spreading of each failure, as a function of morphometric indices generated from his own landslide database.

The percentage of rafts and blocks reported at burst and slide sites reveals little. 'Blocky' deposits alone are noted at 38% of peat slides, and in conjunction with rafts at 6.5%. In comparison, blocks are noted as the lone deposit form at only one burst, and in conjunction with rafts at 51% of bursts. Rafts alone are reported at 12% of bursts and 53% of slides. Only 3.7% of slides have no solid form reported, but 34% of bursts have no solid deposit form recorded. The lack of reporting does not guarantee absence, but this is an assumption that has to be made on the basis of the data alone. It is possible that the lack of reporting of solid deposit forms at bursts relates to the proportionately greater importance attached to fluidised debris by these authors, as noted in Chapter 2. Equally, the greater number of rafts (described as the larger more coherent peat masses) at slides may correspond to greater coherency of deposit at these failures.

Figures 3.10a to c illustrate the axial dimensions (a-, b- and c-axes) of the largest solid deposit at each failure, plotted individually as histograms. Maximum deposit a- and b-axes range widely, from under 1 m in length to in excess of 40 m. c-axes are well spread within a small range of between 0.2 and 2.0 m, which would correspond to realistic peat depths at most of the landslide sites (see section 3.2.4). As a consequence of the considerable range of a- and b-axes, block volumes exhibit a large

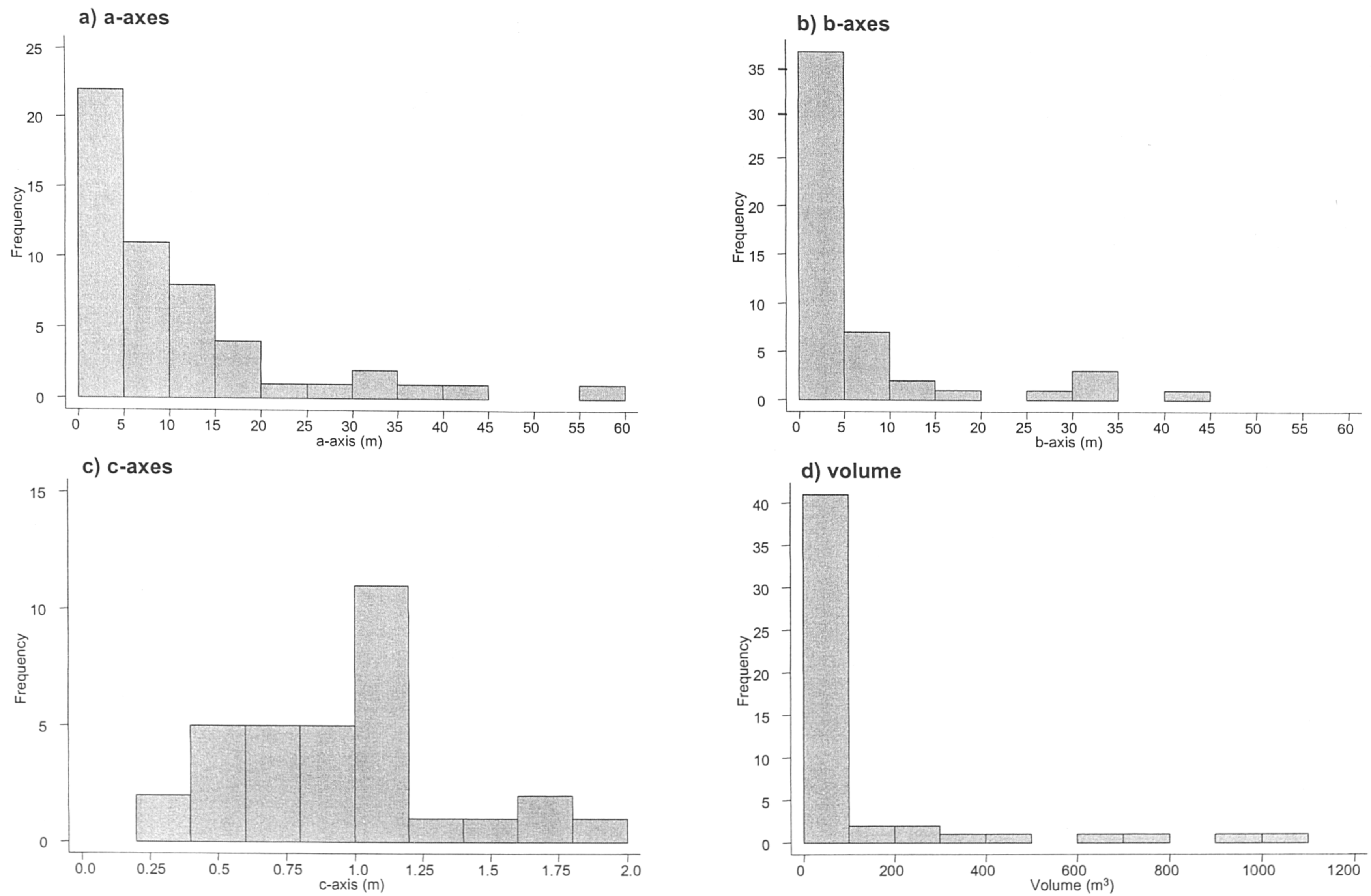


Figure 3.10. Histograms of raft and block deposit dimensions

range, from under one cubic metre to several hundred cubic metres. A majority of blocks are of low volume, under 20 m^3 (Figure 3.10d). There is an approximately linear relationship between a- and b-axes, with a- and b-axes predicting one another well through the full range of solid deposit sizes (r^2: 0.80). The ratio of a- to b-axis length is approximately 1.6.

Slurry is widely reported at both failure types. 85% of bursts and 55% of slides are noted as exhibiting some form of slurried peat deposit. At 15% of both burst and slide sites, there is no consideration of slurried deposit form. At no burst sites was an absence of slurry noted, although 15% of slide reports note the presence of solid deposit in the absence of slurried peat. It is possible that at these latter sites, most of the movement occurred en masse, with break-up into smaller solid constituents, but no remoulding into slurry. The characteristic defining feature of bursts appears to be the presence of liquefied peat, and hence it is unsurprising that it is nearly always reported, or only omitted through the superficiality of study of individual failures. The presence of slurry appears unrelated to either the location of failures within drainage lines (implying wetter peat pre-failure) or to lower slope angle, over which most of the run-out would be expected to occur.

Levees and block-lines are reported at 46% of slides and 20% of bursts, and reported as absent at 35% and 27% respectively. Levees and block-lines suggest a slurried flow in which the larger blocky debris is expelled from the margins of the advancing peaty mass, a snout of material leading the debris trail downslope. While this might occur at both slides and bursts, the proportion of solid deposit is likely to be higher in the distal run-out of slides because of the greater coherence of transported peat. As a result, morphological evidence will be clearer at slides than bursts, and reports of such features correspondingly greater.

The presence and absence of tension features was also noted. Both tears and cracks are found at slides and bursts. Only slides appear to exhibit cracks without tears, and only bursts exhibit tears without cracks. Little process significance can be attached to this subdivision, other than a majority of peat failures exhibit tension features. If these tension features represent a pre-cursor to the formation of discrete solid peat masses, then it may be assumed that a larger area was unstable than that directly transported during failure. The unstable, but untransported area would be defined by the extent to which cracks or tears extend backwards from the scar margins. 81% of crack and tear depths when considered together (because of the sparsity of quantified examples) are 1.5 m in depth or below, with only a few examples extending into deeper peat. The significance of this is better considered in the light of mean peat depths at slides and bursts, examined in the following section.

Scar and deposit length and width are frequently measured or estimated within the peat failure literature, in order to provide an indication of magnitude, and in the approximate calculation of failure volumes. The maximum downslope and across-slope extent of the landslide scars and deposits may indicate the degree of extension and lateral spreading during transport. Figures 3.11a to d indicate that scar lengths range from between 10 m to over three kilometres in the most extreme case. Nearly all failures are under 1500 metres in length, with deposit widths mostly under 400 m, and concentrated at far lower values. Figure 3.12a shows scar lengths and widths plotted using a logarithmic scale, with bursts and slides separated. Slide scars are generally speaking shorter and narrower than bog bursts. The same approach may be taken with deposit lengths and widths (Figure 3.12b). Again, slides and bursts are separated by magnitude, with slides occupying the smaller range of deposit extent, and bursts the larger range.

When slide and burst scar length/width ratios are plotted, slides have a good spread of values between 1 and 17. Bursts are clustered below a length/width ratio of around 5. This suggests that slides are more linear than bursts, which fits with the descriptions generally of more amphitheatre shaped burst disturbance areas. True amphitheatre shapes would have length/width ratios closer to one, but most bursts when observed on air photographs or in the field have extensive scoured out tracks beneath the main 'scar'. Because this is also included in the morphometric assessment of the features, length/width ratios perhaps over-represent the lengths of the major part of bog burst disturbances.

The measurement of scar depth is often undertaken at peat failures, to be used in conjunction with length and width for volume calculations. Depth is also reported in conjunction with stratigraphic profile descriptions used in the consideration of material controls upon failure (see section 3.2.4). Recorded scar depths at slides range between 0.4 m and 6 m in depth, with an average of 1.18 m (s.d.: 0.85). Burst scar depths are greater with a mean of 3.2 m (range: 0.4 to 9 m) and more variable (s.d.: 2.36). There are five examples of burst for which scar depths exceed 5 m, and this suggests either a tendency to over-report depth, or the occurrence of bog bursts in very deep peat systems. Deposit depths are frequently unreliably reported. In the case of bog bursts, it is often the maximum infill depth of gullies or choked stream channels that are noted as an indication of deposit depth. Reporting for slides is more

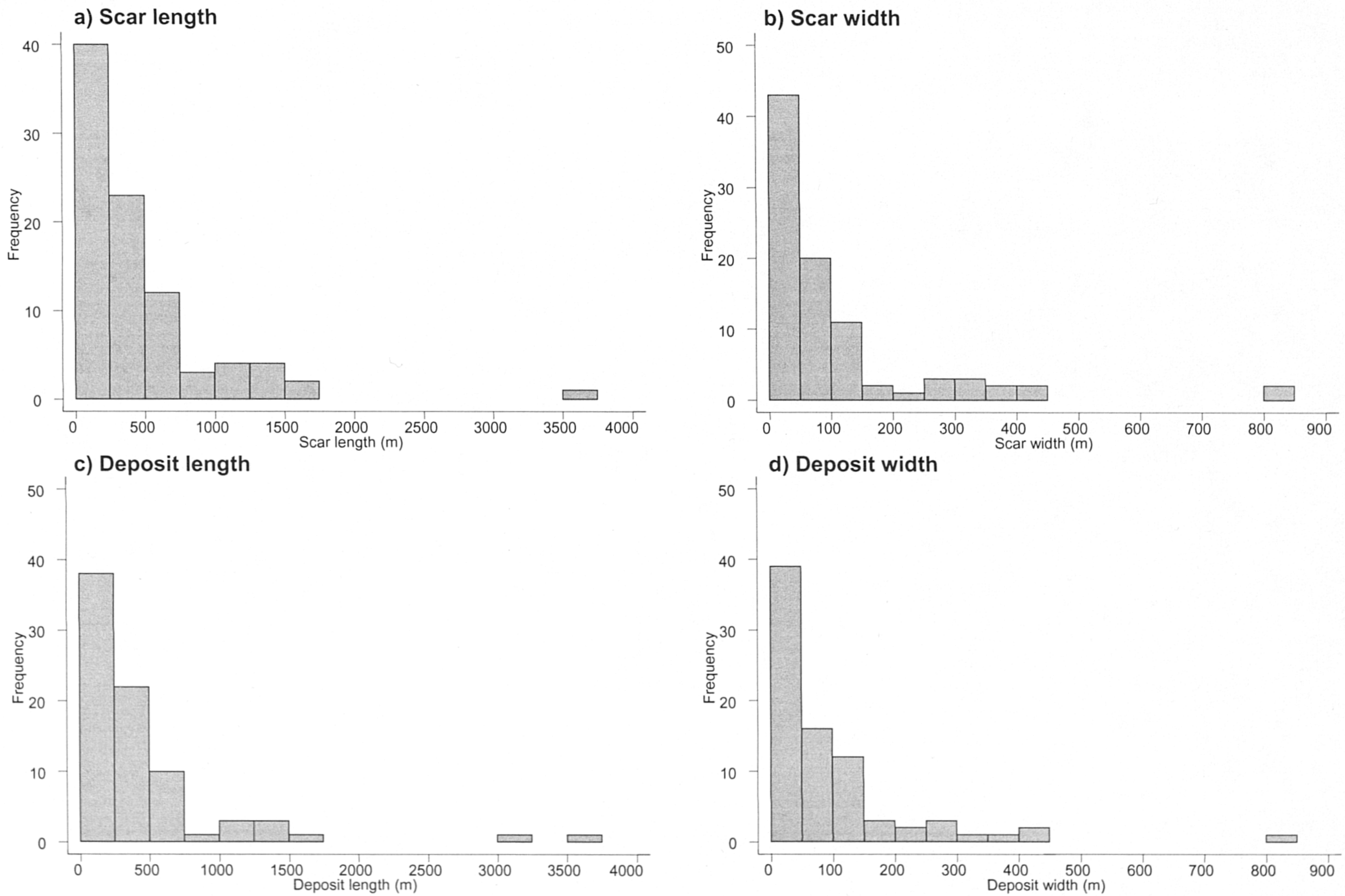
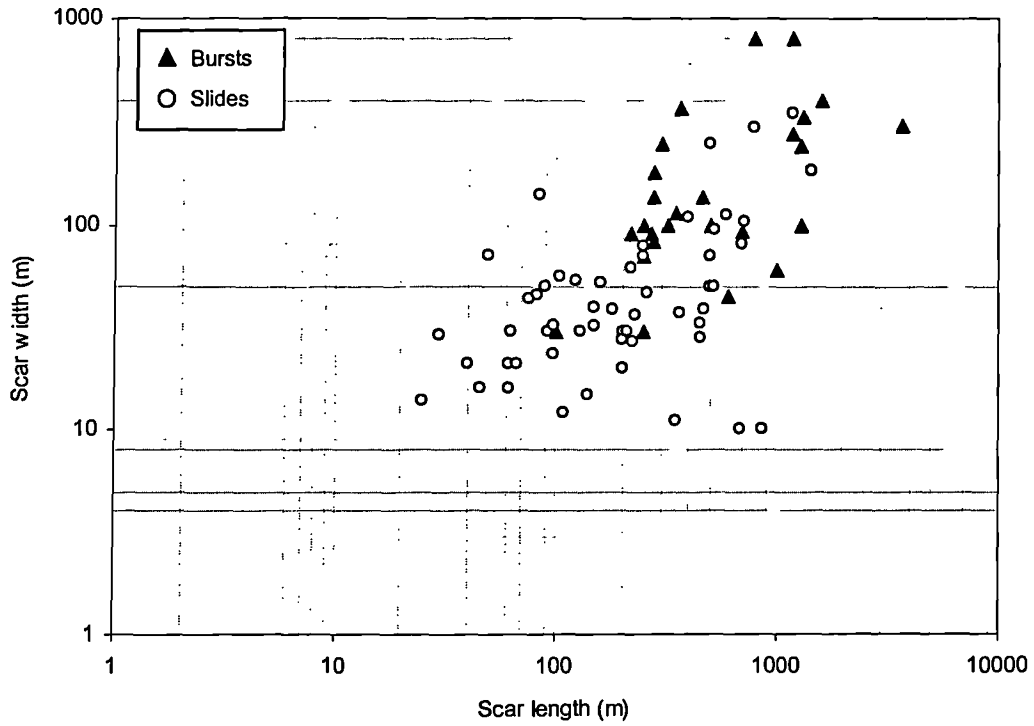


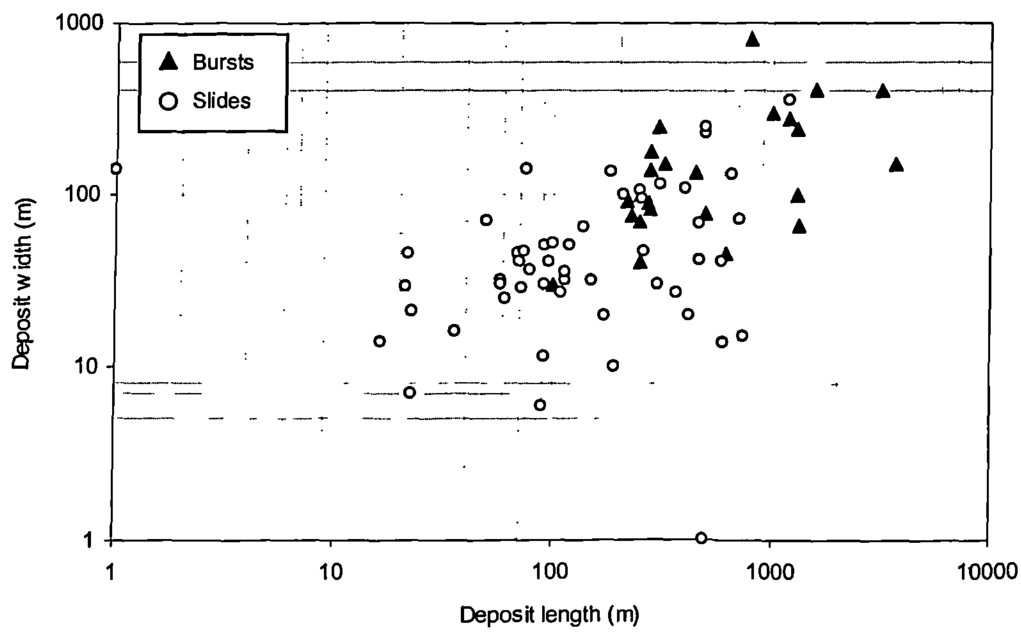
Figure 3.11. Histograms of scar and deposit axial dimensions

Figure 3.12. Scatterplots of scar and deposit axial dimensions.

a) Scar length and scar width for bursts and slides



b) Deposit length and deposit width for bursts and slides



consistently restricted to maximum solid deposit depths (such as block or raft c-axes).

The product of scar width, length and depth is used to estimate displaced volume. Volume is a key parameter used to compare the relative significance of mass movements as hazards or geomorphic agents (Glade and Crozier, 1996; Westerberg and Christiansson, 1999). Figure 3.13 shows displaced volumes of peat for slides and bursts, plotted against the altitudes at which they occur. Bursts are the largest failures, with volumes greater than 10 000 m^3. This suggests that instability is mobilised over larger areas than in the smaller peat slides (generally between 100 and 10 000 m^3). Approximately one quarter of peat slides are under 1000 m^3 in volume suggesting that the displaced areas are relatively insignificant.

Figure 3.14a plots mean slope angle against altitude. Slides occur at higher altitudes than bursts (generally between 300 and 700 m), and over steeper slope angles, between 5 and 20°. Bursts occur in peat at lower altitudes (generally below 500 m and down to sea-level) and usually on slopes below 7°. This corresponds well with many reports of bog bursts in estuarine peat areas, such as the Sarawak failure, (Wilford, 1966) and the Solway Firth failure of 1771 (Pennant, 1772). It also supports the idea that bog bursts may occur well within the geographical extent of many peat deposits, where slopes are gentler than at the margins. Peat slides are associated with greater slope angles in higher altitude areas, and potentially associated with more extreme, orographic rainfall. Slope and altitude differences between slides and bursts may explain the deeper peats found at bursts, and the shallower peats at slides. As slope angle increases, the conditions for peat accumulation deteriorate, and hence peat depths are shallower.

Figure 3.14b represents slope form by plotting upper slope angle against lower slope angle for the scar areas of both bursts and slides. Values falling above the 1:1 line are concave and below are convex. Values falling on the line occur on rectilinear slopes. Peat slides occur across the full range of slope forms (convex, rectilinear and concave), but are associated primarily with concave slopes where slope angle is below 15°, and with convex slopes where slope angle exceeds 15°. This may be a function of the topographic circumstances in which peat is found, with convexo-concave valley sides acting as the setting for many of the recorded slide examples. Bursts are associated primarily with convex slopes over low slope angles and at slightly lower altitudes. Considered together, Figures 3.13 and 3.14 suggest that slides and bursts are characteristic of peat environments under differing topographic settings.

Figure 3.13. Displaced volumes for slides and bursts

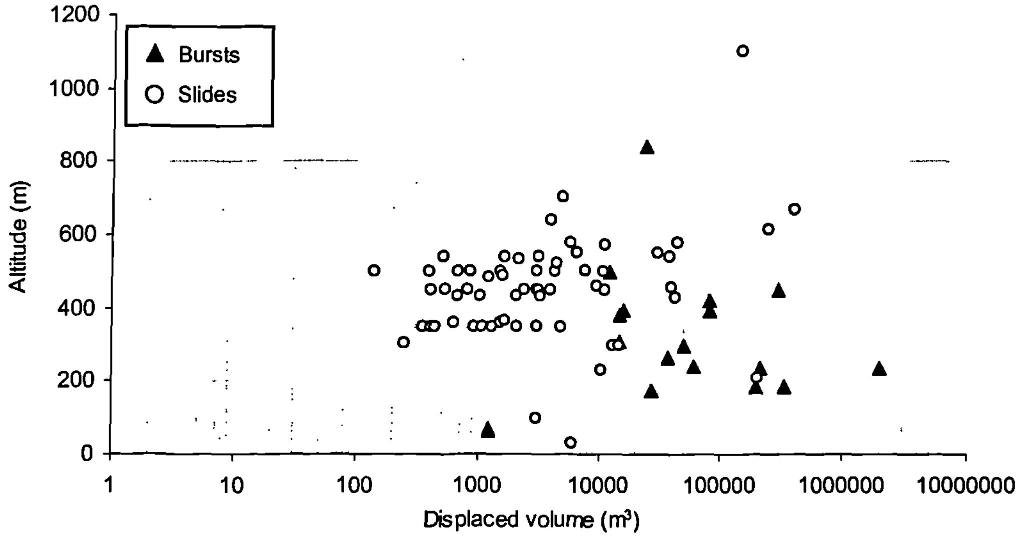
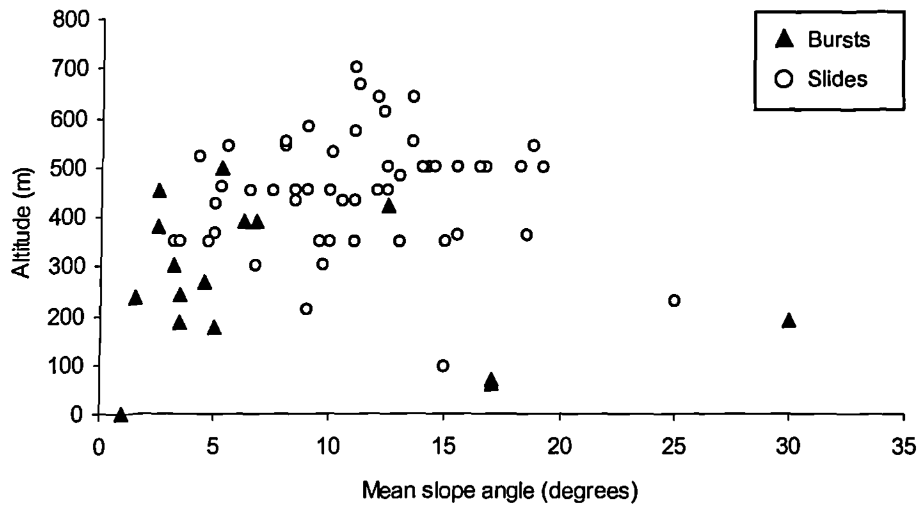
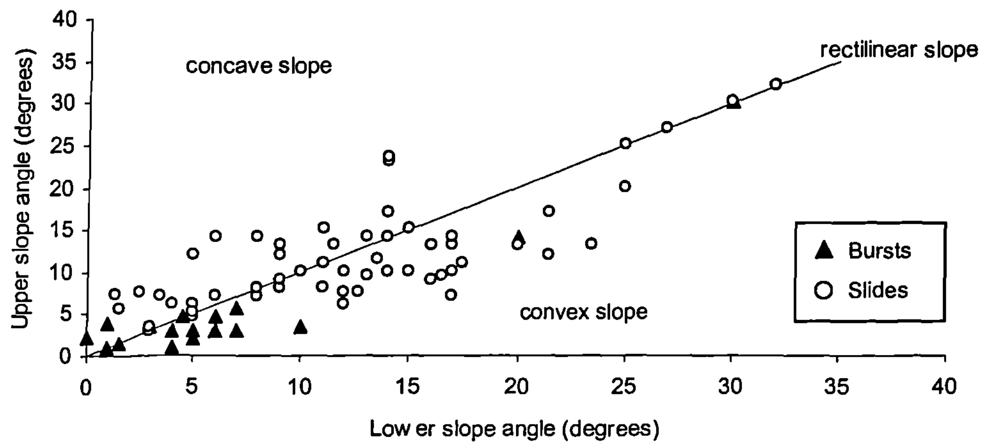


Figure 3.14a) Mean slope angle and altitude for slides and bursts



b) Upper and lower slope angles for slides and bursts



Crozier (1973) proposed the use of two additional measurements of landslide morphometry in addition to scar and deposit dimensions. These are the degree of excavation (Lr) and the total disturbance length (L), shown in Figure 3.8. When all these measures are considered together, seven morphometric indices may be calculated (Crozier, 1973). The procedures by which these indices are calculated (e.g. tenuity, flowage), and their meanings are shown in Table 3.3a. Values for Crozier's test population of failures are compared with values calculated using the same criteria, but applied to peat failures (Table 3.3b). Peat slides are considered as translational slides in the literature, while bog bursts are regarded as more fluid movements. On this basis, index values calculated for slides and bursts should correspond to planar slides and fluid or viscous flows respectively. However, there is little correspondence between the values calculated for peat failures and those for Crozier's test set. Mean values for bursts of 1.14 in dilation and 1.75 in tenuity place them in the viscous-flow category, as do mean values for slides in the displacement (23.89) and tenuity (1.71) categories. However, peat slides may also be considered as slide-flows via dilation (mean: 0.93) and as both viscous and fluid flows using the depth index (bursts mean: 0.56; slides mean: 0.71). It is difficult to say whether the variability in classification relates to morphometric variability within both failure types. It may be that Crozier's classification is inadequate for bursts and slides, or that both types differ significantly in process from any of the previously defined process groups. Previous research into other mass movements has successfully used the index values to categorise process types (Cooke and Doornkamp, 1974; East, 1978)

The underlying principles of extension (tenuity), lateral spreading (dilation) and excavation (displacement) should still apply to peat failures, even if the index values fall outside Crozier's (1973) calibration set. Figure 3.15 illustrates lateral spreading and extension plotted against one another for both failure types. Tenuity values greater than 1 indicate that the total deposit length is greater than the total scar length, and hence that extension has occurred in transport. A majority of failures of both types exhibit extension. Similarly, dilation values greater than 1 indicate lateral spreading, with values under one denoting confinement. Many failures fall on or below a value of '1' suggesting no spreading, or even confinement relative to the scar width. Local variability in microtopography may act to confine debris in chutes. This is increasingly likely in blanket margin failures discharging into valley sides undergoing dissection.

The displacement index suggests that peat slides experience far greater evacuation of peat debris than do bog bursts (slides mean: 23.89; bursts mean: 0.07). However, this is largely a function of the inadequacy of the morphometric criteria for measurement of

Table 3.3 a) Crozier's morphometric indices for process definition: calculation and justification. Calculation values (e.g. *D, L, Wx...*) are shown diagramatically on Figure 3.8.

Index	Calculation	Use
Depth	$\frac{D}{L} \times 100\%$	Relative measure of surficiality
Dilation	$\frac{Wx}{Wc}$	Measure of degree of lateral spread
Tenuity	$\frac{Lm}{Lc}$	Measure of degree of downslope spread
Flowage	$\left\lvert \frac{Wx}{Wc} - 1 \right\rvert \frac{Lm}{Lc} \times 100\%$	Measure of bi-axial spread
Viscous Flow	$\frac{Lf}{Dc}$	Measure of the bare surface exposed over evacuated area
Displacement	$\frac{Lr}{Lc}$	Measure of degree to which displaced mass has evacuated the surface of rupture
Fluidity (water content)	Ranked residuals from regression of flowage on slope	Measure of fluidity or water content

b. Comparison of database and Crozier's summary values for morphometric indices

Index	Summary statistic	Rotational Slide	Planar Slide	Slide-flow	Viscous-flow	Fluid-flow	Bog burst	Peat slide
Depth	**M***	24.23	7.66	4.98	3.34	1.47	**0.56**	**0.71**
	Sd*	19.28	5.92	1.95	1.39	1.00	**0.54**	**0.68**
Dilation	**M**	0.99	0.95	0.94	1.09	0.89	**1.14**	**0.93**
	Sd	0.10	0.09	0.19	0.37	0.41	**0.79**	**0.68**
Flowage	**M**	-	-	16.01	5.39	12.14	**90.16**	**71.60**
	Sd	-	-	5.88	4.57	10.59	**116.52**	**210.85**
Displacement	**M**	68.10	79.87	56.89	29.28	59.06	**0.07**	**23.89**
	Sd	12.03	6.00	20.47	30.30	30.87	**0.38**	**45.14**
Viscous-flow	**M**	-	-	-	3.66	-	-	-
	Sd	-	-	-	2.41	-	-	-
Tenuity	**M**	13.19	1.17	3.07	1.71	3.33	**175.00**	**1.71**
	Sd	24.15	0.04	0.20	0.71	1.94	**0.95**	**1.80**

* **M**: mean
Sd: standard deviation
-: data absent in Crozier's work

Table 3.4a. Correlation matrix for all burst morphometry parameters

	length (scar)	length (disturbance)	length (deposit)	length (excavated)	width (scar)	width (deposit)	depth (scar)	depth (deposit)	upper slope angle	lower slope angle	volume
length (scar)											
length (disturbance)	0.5467										
length (deposit)	0.5544	**0.9964**									
length (excavated)	.	.	.								
width (scar)	0.0362	0.3781	0.3842								
width (deposit)	0.0282	0.0469	0.0490		0.3516						
depth (scar)	0.0113	0.0924	0.0907		0.2423	0.3252					
depth (deposit)	0.0104	0.0340	0.0330		0.0228	0.1894	0.6374				
upper slope angle	0.1807	0.1547	0.1492		0.2905	0.3383	0.1008	0.0213			
lower slope angle	0.1148	0.1163	0.1031		0.2139	0.2715	0.1557	0.0635	**0.8381**		
volume	0.0452	0.2797	0.2793		0.1716	0.3705	0.3756	0.0343	0.0752	0.0799	

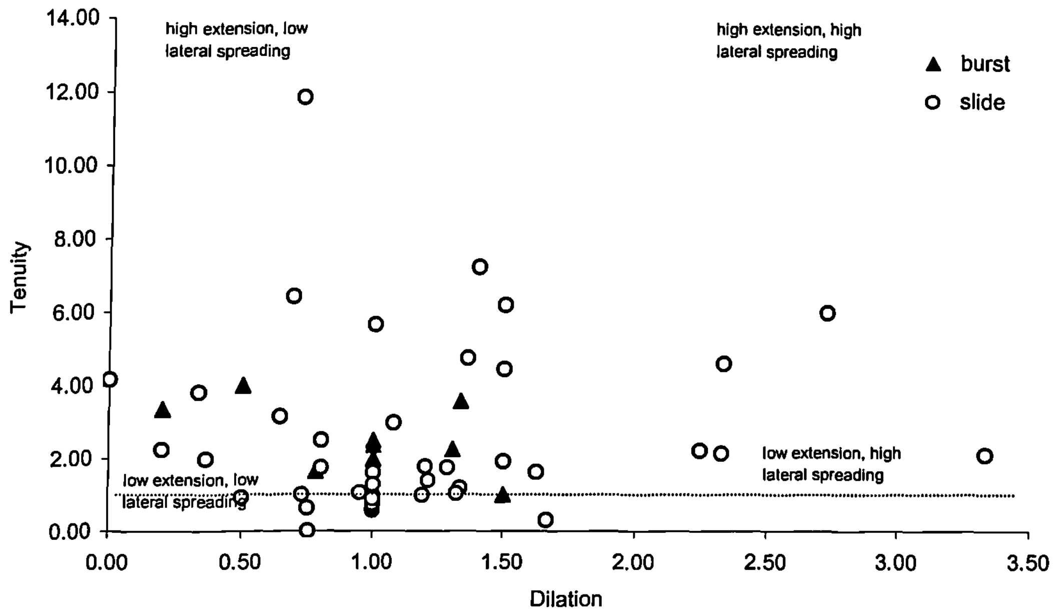
NB: bold relationships: significance level = 0.361, n = 30)

b. Correlation matrix for all slide morphometry parameters

	length (scar)	length (disturbance)	length (deposit)	length (excavated)	width (scar)	width (deposit)	depth (scar)	depth (deposit)	upper slope angle	lower slope angle	volume
length (scar)											
length (disturbance)	**0.6685**										
length (deposit)	0.5131	0.4586									
length (excavated)	0.1138	0.3669	0.0259								
width (scar)	**0.8078**	0.5727	0.4880	0.0719							
width (deposit)	**0.7413**	0.4721	0.4929	0.0260	**0.8864**						
depth (scar)	0.0465	0.1425	0.0671	0.0519	0.0567	0.0724					
depth (deposit)	0.0612	0.1925	0.0694	0.0464	0.1000	0.1045	0.5144				
upper slope angle	0.0629	0.1816	0.1210	0.0388	0.0552	0.0566	0.0978	0.0590			
lower slope angle	0.0061	0.0779	0.1255	0.0001	0.0073	0.0126	0.2484	0.1009	0.2913		
volume	**0.8669**	0.5446	0.3827	0.1175	**0.8512**	**0.7686**	0.0731	0.0764	0.0162	0.0003	

NB: bold relationships: significance level = 0.235, n = 70)

Figure 3.15. Dilation and tenuity for slides and bursts



burst sites. The measurement 'Lr' (Figure 3.8) is based upon the distance from the scar head to the uppermost limit of the deposit. In the case of bog bursts, the scar head is often spatially ambiguous because of the heavily crevassed nature of the entire disturbance zone. Equally, raft displacement is minimal at the uppermost 'head' limit of the scar, and there may be less than one metre of excavated surface. This produces very low displacement values by Crozier's scheme, but does not represent the actual degree of excavation, which when summed for all the minor raft displacements may be extensive. This represents the difficulty in defining a discrete scar boundary at bog burst sites rather than a criticism of Crozier's morphometric indices.

Further exploratory data analysis, attempting to relate upper and lower slope angles to scar, deposit and disturbance lengths add little to the discussion. No significant relationships are demonstrated between them. Tables 3.4a and 3.4b show correlation matrices for bursts and slides to this effect, with the correlation coefficient, r, tabled. The previously noted strong linear correlations between scar lengths and widths and deposit lengths and widths are shown highlighted in bold.

3.2.4 Slide and burst mechanisms

The initiation and mechanisms of slide and burst movement are most likely to be governed by material properties and drainage conditions immediately prior to, and during failure. These factors are summarised in the 'Material Characteristics' and 'Drainage Setting' sections respectively. Analysis is presented here that deals specifically with data from these two sections, but which also relates material and hydrological characteristics to other database variables. No data exists for the material conditions prior to failure at any of the peat failure sites, for the obvious reason that no forewarning of failure was available to suggest a need for sampling.

Geotechnical data are available for only nine of the mass movement events (Table 3.5). Of these, three are peat slides with a failure plane hypothesised as occurring at the peat-substrate interface (Langdon Head, Carling, 1986; Cuilcagh, Dykes and Kirk, 2001; Hart Hope, Warburton and Higgitt, 1998). One exhibits slide morphology with a failure plane within the peat, namely one of the Skerry Hill failures (Wilson and Hegarty, 1993), and three are artificially triggered or engineering failures (Ward, 1948; 1955; Hungr and Evans, 1985). The latter examples are slumps rather than slides or bursts. Geotechnical data are reported for two bursts only (Alexander *et al.*, 1985; Hendrick, 1990). The variability in both failure type and perceived location of failure plane severely limit the value that interpretation of these results might provide.

Moisture content and dry unit weight are the most consistently reported values. Moisture content ranges between 58% and 64% of dry weight for the clays underlying failed peat masses, and between 560% and 1050% for peats experiencing failure. In some cases, the authors do not make clear whether the percentage moisture content is a dry weight value, or a volumetric measure of moisture content. Differences in the measurement and expression of bulk properties may also explain the great diversity in unit weight values across the small population of failures (from 9.9 kN m^{-2} to 240 kN m^{-2}). It is difficult to say whether some extreme values are anomalous or products of variability in the means of laboratory testing or data preparation.

The angle of internal friction (ϕ), and cohesion (*c*) values are quoted for five of the failures. These are the parameters most frequently used as the basis for slope stability analyses, and may be expressed according to the factoring in of pore-water pressures. Discussion of the derivation of these values is particularly limited in some reports (e.g. Hungr and Evans, 1985; Hendrick, 1990), with no information available regarding the test conditions, nor the loads applied. The values that have been produced suggest lower cohesive strengths in the peats (0.62 - 8.74 kN m^{-2}) than in the clays sampled (2.75 - 9.75 kN m^{-2}). Angles of internal friction show a similar trend, describing the slopes in excess of which the tested material may be considered unstable for the drainage scenarios used during testing. Peat angles of internal friction range between 13.5 and 18°, while those for clay range between 14.4 and 26.5°. These values correspond reasonably well to the slope angles at which peat slides experience failure, but are far in excess of the relief in which bog bursts are situated. The four sets of parameters, taken together suggest that peat is less dense, wetter and weaker than the underlying clay, although the major disparities are manifest in bulk properties rather than properties directly associated with material strength. The presence of a consistently weak layer at the base of the peat, or in the substrate is not shown by these values. In addition, the data set is particularly small when compared with other parts of the database.

An alternative but popular means of representing material characteristics at peat failures relates to stratigraphic profiles taken at scar heads. These describe the major peat and soil units, usually in terms of their fibre content and perceived degree of humification. Formalised schemes of peat classification (such as that of von Post, 1924) are rarely used, and bulk properties are not usually provided. Figure 3.16 shows maximum recorded peat depths at all bursts and slides, and Figure 3.17 provides a graphical summary of stratigraphies for most of the available bog burst data, and for field surveys of a sample of peat slide scars.

Bog bursts clearly exhibit a greater range, and deeper maximum peat depths than peat slides. Peat slides occur most frequently at depths between 0.5 m and 1.5 m, while bog bursts range between 1.0 m and 5.0 m. There is some justification for a depth-based discrimination of the two forms. Forms occurring in peat of under 1.5 m in depth may generally correspond to slide morphology, while those of 1.0 m in depth or more may represent bog bursts. The presence of deeper peat may relate to the location of bog bursts relative to peat slides in the peat blanket (blanket centre as opposed to blanket margins).

The often cited two-phase peat system of bog bursts is clearly demonstrated by the stratigraphies shown (Figure 3.17). Fresh fibrous peat to nearly one metre in depth overlies an equivalent or deeper layer of humified or amorphous peat. Most stratigraphic records do not note the nature of the substrate, usually because it is not exposed in failure, and assumed to be of little direct relevance to the failure mechanism. The Glendun profile was compiled for the case study described later, in Chapter 8. When compared with peat slide profiles, stratigraphies for bog bursts appear simplistic. Peat slides exhibit greater complexity in juxtaposition of layers, and over smaller ranges of peat depth. The dual-layer system of bog bursts contrasts with profiles of three or more layers at slides. Clay/peat layers associated with past mineral inwash horizons are evident, as are local layers of crumbly granular woody peat, and highly humified peat layers with some wood fragments. The substrate is frequently exposed at these sites and is included as part of each slide profile. The material disparity between bursts and slides supports the notion of a weak, highly deformable lower peat mass in bursts, and the presence of a thinner locally weak layer in slides. This latter layer has been suggested to be a sandy clay at the top of the substrate on some occasions (Tomlinson and Gardiner, 1982) and has yet to be tested geotechnically (Carling, 1986).

	Within peat mass	At peat-substrate interface	Within substrate	Unknown/ unspecified
Slide	8.9	49.4	8.9	32.9
Burst	32.7	16.3	0.0	16.3

Table 3.6. Location of failure plane for all peat failures

Figure 3.16. Maximum scar peat depths for slides and bursts

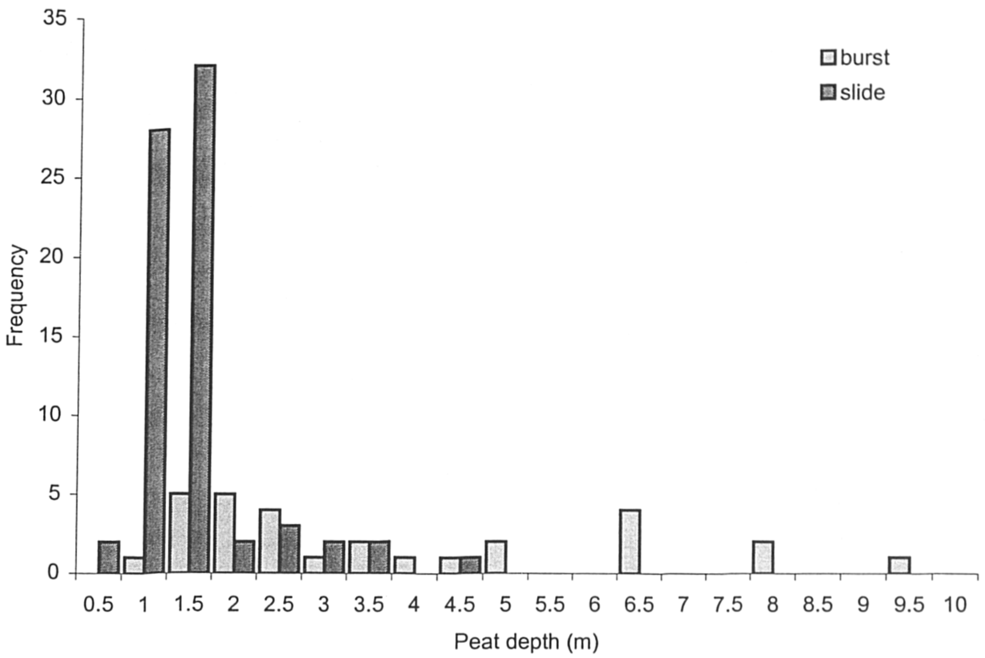


Table 3.7. Hydrological setting for all failures

	Drainage into head and margins	Drainage lines below scar	Drainage into margins	Drainage line within scar	Drainage unreported	Not known
Slides	3.8	6.3	3.8	30.4	46.8	8.9
Bursts	2.0	12.2	2.0	10.2	26.5	46.9

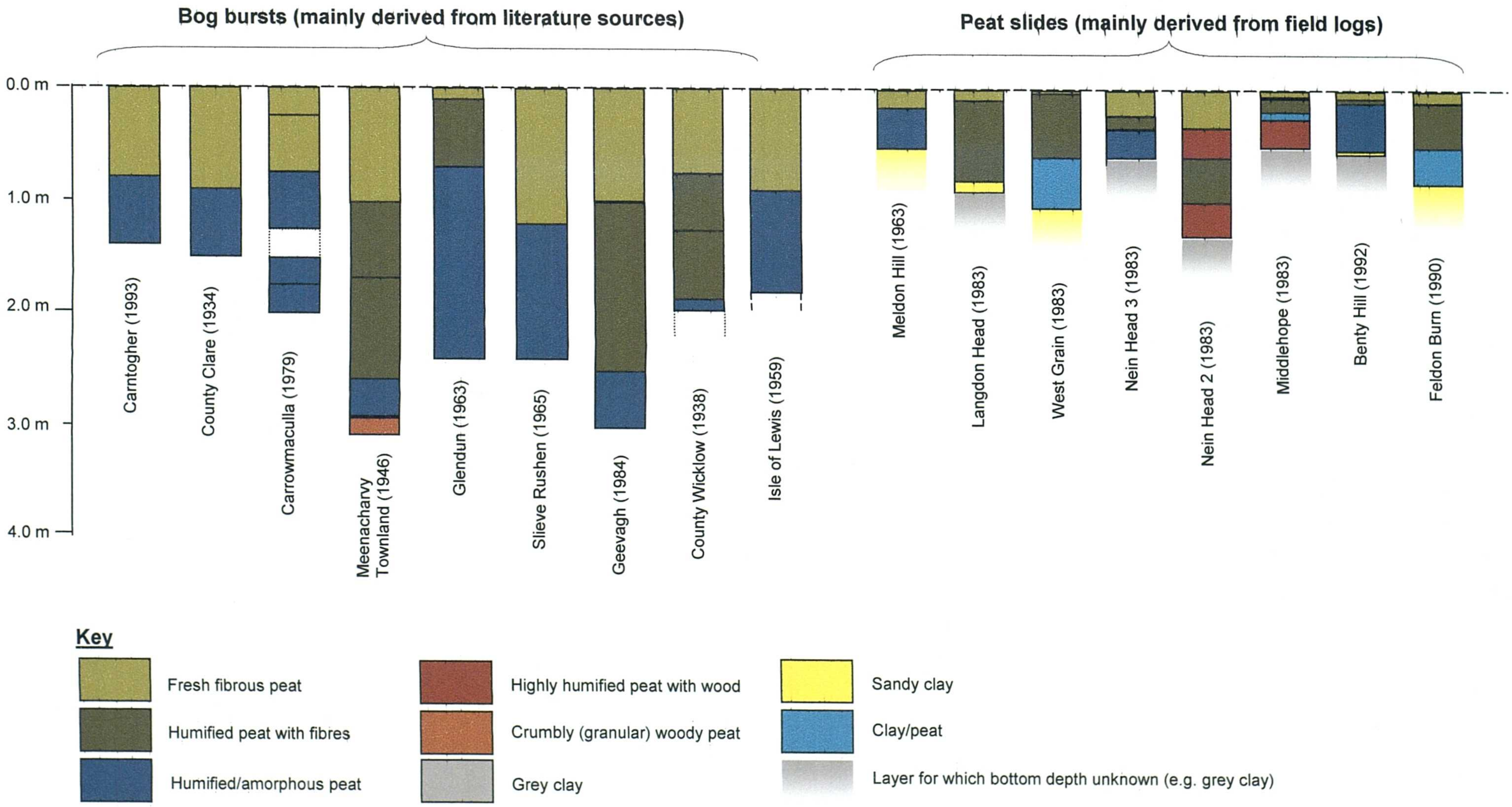


Figure 3.17. Schematics of peat stratigraphy for bursts and slides

The layer directly involved in failure initiation within which a threshold of strength is exceeded, is frequently recorded as the 'failure plane'. In peat slides, just under 50% of all failures are suggested as initiating at the peat-substrate interface with just under 10% noted with failure planes within the peat, or within the substrate (Table 3.6). None of the bursts on record is described with a failure plane within the substrate, with approximately 32% of failures stated as initiating within the peat mass. There appears to be a greater degree of uncertainty over the failure plane location in bursts. It is likely, given the exclusively peaty composition of the failed materials, and the lack of substrate exposure at bog bursts sites (in the absence of dissection, see Figure 3.18) that the percentage of failures initiating at the peat-substrate interface will be more of a minority.

Peat failures may also be examined with respect to the influence of local drainage features, both natural (pipes, flushes, gullies) and artificial (moor drains, cutting). Increased moisture contents are generally viewed as a destabilising influence in slope stability studies, and all of these drainage features may act to increase water contents in areas into which they discharge or through which they pass. Table 3.7 shows the hydrological setting of slides and bursts according to the schematic in Figure 3.6. 30.4% of slide scars contain former drainage lines, as do 10.2% of bursts. More consistent with the bog burst literature are the presence of active drainage lines below 12% of the failures, supporting the possibility of undercutting or the presence of a weak retaining wall of peat. Artificial drainage lines in the form of gripping, and unintentionally as cuts (for fuel harvesting) are recorded as present at 36% of bog bursts, and at only 4% of peat slides. These are pictured in Figure 3.19. Attempts to associate measures of scar morphometry (e.g. linearity) with presence of drainage location revealed little for bursts. However, for peat slides, sites occurring within drainage lines exhibit a strong linear relationship (r^2: 0.92) between scar length and width. In these cases, scar length is 1.6 times more than width. Scars occurring in the other drainage classes have more scattered length/width ratios. The physical basis for this tendency towards elongate forms may relate to the linear nature of drainage lines. A zone of destabilising influence associated with a drainage line would propagate along the line, but only to a limited extent away from it.

Piping is reported at just over one quarter (27%) of peat slides, and at only 4% of bog bursts. Pipe dimensions vary considerably. Most pipes are under 20 cm in diameter, with only a few very large pipes exceeding 0.5 m in cross section. 70% of pipes recorded are singular occurrences within the scar margins, while the remaining 30% are recorded as multiple features. Both the limited number of pipes, and the restraint

Figure 3.18. Substrate exposure on incision of peat substrate. a) stone lines indicate foci for drainage at Skerry Hill peat slide (unusual in its 'within' peat mass failure plane); b) substrate exposure at margins of Slieve-Rushen bog burst (arrowed).

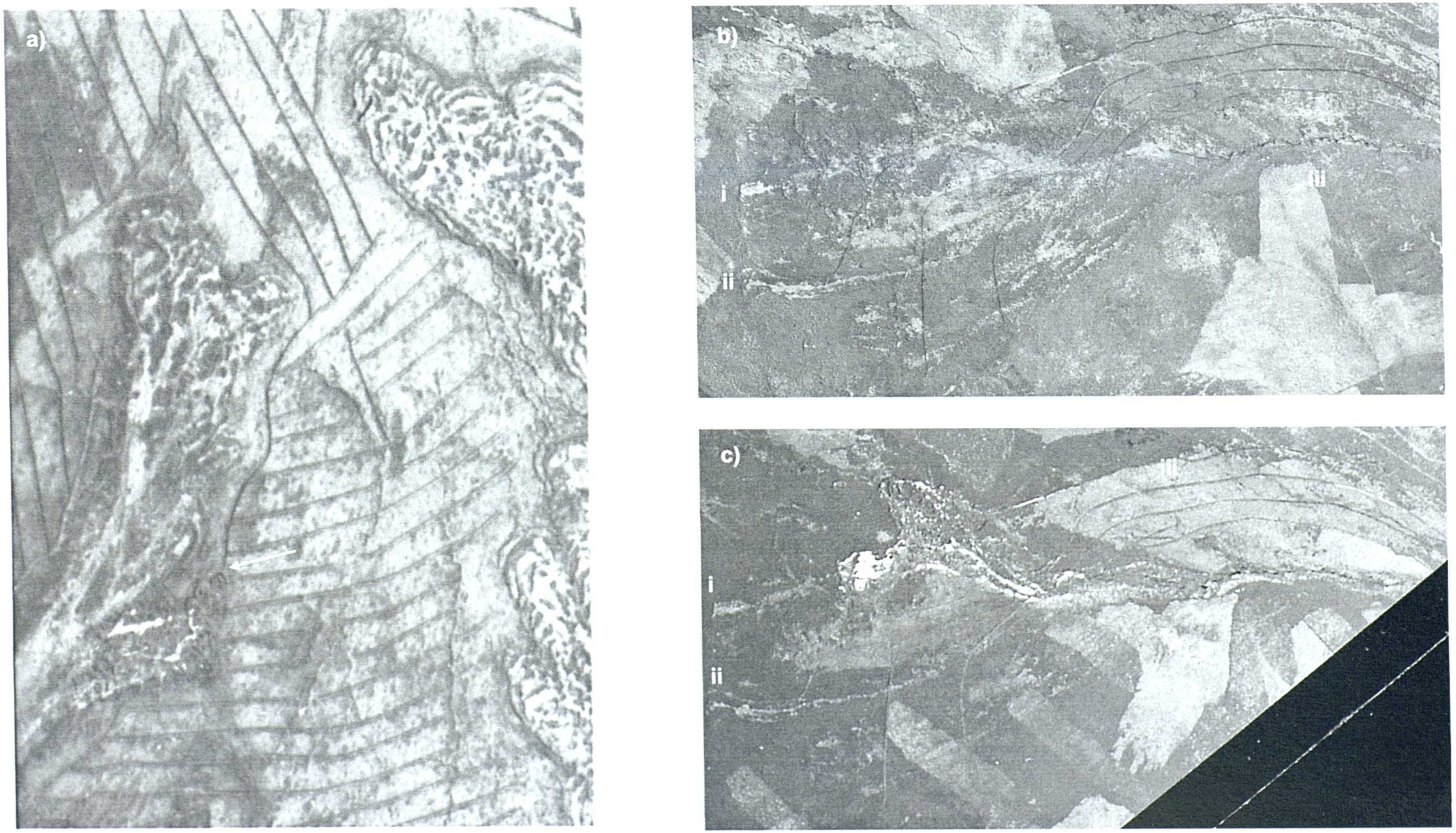


Figure 3.19. Grips and natural drainage at bog burst and peat slide sites: a) Beaghs Head failure to the back of Glendun - artificial drainage cut after failure is clearly visible surrounding the heads of both failures. The intense pattern is likely to affect the bog surface water regime considerably. The arrow marks the scar area fed by the grip, also arrowed on Figure 3.7c; b) Feldon Burn peat slide - the upper image shows the blanket two days before failure, with natural flushes i) and ii) drained by arcuate grips, c) the lower image shows the failure head situated within flushline i) and crossing three major grips (iii).

on potential discharge imposed by their dimensions suggests that pipes are unlikely to be highly influential, except where they are very large. Some caution must be exercised in the consideration of drainage features, as pipes may develop in the cracks formed during failure, while drainage lines may be cut as a remedial measure (e.g. Figure 3.19).

The effectiveness of drainage lines in transmitting water to unstable peat masses will be limited as a function of supply. The short and long term climatic conditions leading to failure are sometimes recorded for peat failures, including magnitude and duration of rainfall events. In addition, the seasonality of failure may provide some indication of the wider moisture regime of the peat blanket environment. Aspect and altitude may also be important in terms of exposure of failed sites to weather fronts, and to receipt of solar radiation during snowmelt. Climate effects will be variable regionally (and locally in steep environments). Attempts to derive significant relationships between climatic variables and failure characteristics must be regional in order to have any physical basis.

Regional subdivision of scar aspect for a UK group of failures revealed no significant tendency for preferred failure orientation. This suggests that the supply of triggering rainfall is not aspect driven. An alternative approach to considering climate divides the year into four equal-length three-month periods, based on suggested causative climatic characteristics, such as rainfall type, and amount. Table 3.8 shows that a majority of peat slides occur within the summer months of June, July and August. Bog bursts are more evenly spread throughout the year. Generally, availability of climatic data for both event types is quite limited as a percentage of the total populations concerned.

Where climatic data is available, it is usually patchy, spatially and temporally. Rain gauges may be significant distances from the sites and of a low resolution, taking daily measurements rather than hourly records. The implication is that magnitude, intensity and duration will be misrepresented. There are a number of rainfall totals based upon spurious water level changes in standing vessels (e.g. buckets or bins), known to be empty prior to storms associated with failures. Even where data is available, the format in which it is presented may not be comparable from event to event. Rainfall amounts are reported as millimetres per hour, a millimetre total for a range of hours (e.g. Carling, 1986: 104.8 mm in 2.5 hours), a cumulative total for days prior to the event (e.g. Mitchell, 1935: 65 mm in 7 days), or a percentage in excess of mean rainfall amounts for weeks or months (e.g. Crisp *et al.*, 1964: 162% of average June rainfall). Rainfall amounts as opposed to intensity are usually described as anywhere between

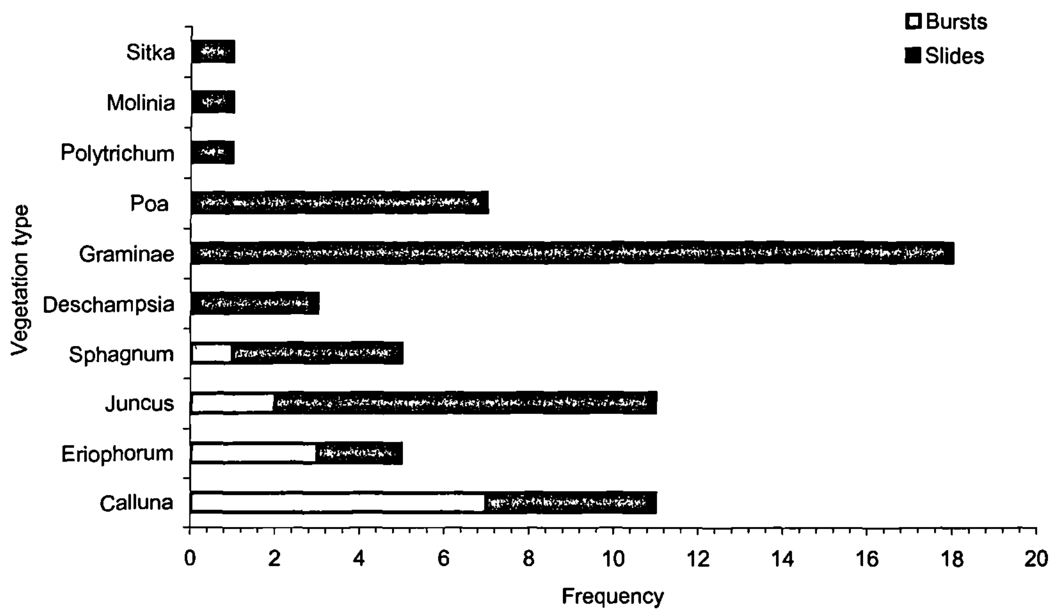
Table 3.8. Grouping of slides and bursts by season

	Winter	Spring	Summer	Autumn	Unknown
Slides	6.3	3.8	46.8	11.4	31.6
Bursts	12.2	4.1	12.2	22.4	49.0

Note

Winter (December, January, February): coldest three months, most likely snowfall (and snowmelt)
Spring (March, April, May): wettest three months, most likely saturated conditions
Summer (June, July, August): driest three months, most likely convective storms
Autumn (September, October, November): defaulted by other seasons

Figure 3.20. Main vegetation types at 'recovering' peat failures



'above average' for the weeks prior to failure, to 'extreme' in the short period prior to the assumed time of failure. Snowmelt has also been clearly implicated in some studies (Warburton and Higgitt, 1998). No information is available about the timing of failures with respect to the peak intensity of storms. Nevertheless, there is a general assumption that failures occur at the maximum intensity attained in each rainfall event. In the case of bog bursts, there are occasional reports of failures which are not associated with above average rainfall. While there are some 'classic' papers deriving thresholds for landsliding related to rainfall intensity (e.g. Caine, 1980; Crozier, 1999), the data is simply not available in the peat landslide literature to adopt a similar approach.

3.2.5 Recovery of slide and burst sites

The recovery of peat failures is rarely discussed in the literature, and much of the data presented here relates to field surveys carried out at sites previously studied in a geomorphic context. This brief summary represents more of a starting point to recovery research than the retrospective analyses described previously. It is hoped that enough data will exist in the future that the 'duration' category will act as a useful benchmark against which to analyse vegetation development.

Figure 3.20 highlights the main vegetation types found at recovering slide and burst sites. Frequency denotes the number of occasions each species is reported in association with material *within the scar areas.* Although vegetation patterns surrounding failure scars are occasionally described to provide an ecological context, reports of species from within the scar are few. In general, the species noted for bursts are those typical of waterlogged, peaty surface conditions, including the peat forming *Sphagnum* spp. and *Eriophorum* spp. The grasses (*Molinia/Graminae*) and other species shown mainly at slides are found over drier terrain, and are not indicative of conditions conducive to peat formation. There may be both climatic reasons and morphological reasons for the differing slide/burst patterns. At bursts, there is a greater quantity of peat remaining in the aftermath of failure which may encourage recolonisation by bog accumulating species. Furthermore, many of the bursts (relative to slides) occur in Ireland, where the climate is slightly wetter, and better suited to *Sphagnum* and *Eriophorum*.

There are limitations to this portrayal however, key among which is the lack of temporal reference for each vegetation type. For example, the high presence of *Graminae* spp.

at slides relates to the revegetation of their clay scars, often years later. Conversely, the limited excavation at burst sites means that *Calluna* spp. are found as part of the 'recovery sequence' immediately after failure, on top of the blocks that still comprise the scar area. The make up of block tops relative to bare peat tears may change with the break in hydrological continuity that characterises burst areas. Hence, *Calluna* may actually decline in the years subsequent to failure. A larger data set incorporating more field study or greater focus on recovery is needed for further elaboration.

Factors other than vegetation operate or are present at failure sites, providing information about the relative states of geomorphic, ecological and pedological activity. The stabilisation by vegetation of peat deposits left stranded on the scars (blocks or bare 'floes') is the most frequently reported factor (80% of slides, 30% of bursts). Early stages of soil development, and the presence of ponding are also noted. Seasonal ponds may provide habitats capable of supporting aquatic species, including the presence of *Eriophorum spp* in their immediate locality. It is unsurprising that ponding is reported more frequently at bursts (45%) than at slides (22.5%), given the presence of extensive enclosed fissures in the forms of tears, and the probable poor permeability of the peat mass surrounding each fissure. Soil development may initiate through the formation of aggregates in reworking of surface clays, and the exposure of the formerly waterlogged substrates to oxidation. It is probably reported more widely at slides (35%) than bursts (28%) because of the presence of appropriate mineral parent materials exposed after failure.

Factors detrimental to recovery are also noted. Burning and grazing may prevent the development of vegetation, and while the former is infrequently reported (less than 5% of both slides and bursts), grazing by sheep is prevalent at many sites (60% of slides, 12% of bursts). Dissection by rills and gullies, and small-scale sheet erosion may prevent the establishment of vegetation, as well as continue to export sediment from the landslide scars. The continuation of geomorphic activity subsequent to failure is reported far more for slides (59%) than for bursts (22%), and this may well relate to the steeper slope angles at the former. Secondary failures, referring to side slumping of scar faces, or localised reactivation of peripherally unstable peat are noted for some failures (30% of slides, 20% of bursts). Through the generation of peat floes, they may contribute to long term stability rather than the short term manifestation as instability.

3.3 Research directions and hypothesis generation

The database provides a unique combination of peat mass movement data and generates several important research questions. This section considers the key findings of the database, and uses them as a means to generate hypotheses attending to gaps in knowledge of peat mass movements. Hypotheses are grouped according to morphology, mechanisms and recovery.

Analysis of slide and burst morphology revealed several similarities and several disparities between the two forms (section 3.2.3). Slides tended towards linear scars, whilst bursts exhibited more rounded disturbance areas. Slides displaced smaller volumes of peat than bursts but at the same time, experienced far greater excavation of their scar areas. A reasonably clear topographic distinction was evident for the location of slides relative to bursts, on the basis of both slope angle and altitude. Blocks/rafts exhibited a characteristic form ratio in which a-axis length was approximately 1.6 times greater than the b-axis length. Maximum dimensions for non-slurried deposit (namely rafts and blocks) suggested no criteria for a distinction between slides and bursts on the basis of deposit form. The type of deposit (slurried or solid) could not be related to the origin of failures within wetter peat, such as drainage lines. All types of deposit were noted at both slides and bursts. Hypotheses specific to morphology and morphometry are now defined, and the research implication of each hypothesis considered:

i) There is no form-based justification for a two-fold division of solid deposit into blocks and rafts.

The implication of this statement is that there is no deposit-based form criteria for differentiating peat slides and bog bursts. Block/raft form must be fully assessed if either are to be considered useful as features of process significance at failed sites.

ii) Peat slide blocks exhibit characteristic elongate forms, in which axes parallel to the ground surface (length and width) are greater than the axes normal to ground surface (depth).

This statement implies that there is either a) some organisation to the break-up of the peat mass during failure initiation, or b) a spatially widespread process responsible for break-up of debris during transport and deposition. Because the form ratio of both bursts and slides is similar, either or both of these ideas may hold true at both landslide types.

iii) The presence of slurry is independent of slope angle or former drainage conditions within the undisturbed failure scar.

This hypothesis would suggest that either a) slurry is a product of something other than rate of remoulding of solid deposit, or b) that slurry is present prior to failure, and simply released from within the peat mass during transport. Slurry quantities should be assessed or estimated, and pre-failure conditions investigated where the information is available.

iv) Peat slide deposits collectively exhibit extension in transport, but little lateral spread.

This statement has implications for the debris transport process. Material undergoing transport tends to spread out where the volume of material exceeds the capacity of the current transport vector to accommodate it. This means that should the rate of material supply exceed the rate of transport of it along a particular flow path, the excess material will seek alternative routes for movement, and spread laterally or overtop the material ahead of it. This will be manifest as either block stacking, or lateral spreading. Lateral spreading has already been largely dismissed as a feature in peat transport. Full delimitation of deposit extent should be attempted wherever possible.

v) All peat slide scars are characterised by a high percentage excavation of their scar areas.

vi) All bog burst scars are characterised by a low percentage excavation of their scars.

Confirmation of these hypotheses would provide a key morphological distinction that might be used in the differentiation of form type. There is likely to be a gradation of form between a barely excavated bog burst and a fully excavated peat slide scar. Forms falling towards the middle of this range might not be separated on the basis of excavation alone, highlighting the need for other differentiating criteria.

vii) Peat slide morphology results where failure occurs on slopes in excess of 5° and at altitudes over 300 m.

viii) Bog burst morphology results where failure occurs on slopes under 7°, and at altitudes below 500 m.

These two hypotheses do not provide a slope-dependent criteria for the distinction of slides and bursts, as there will be overlap of features between 5° and 7° and between 300 and 500 m altitude, as well as outliers in both populations. They do provide an easily assessed topographic basis for estimate of most-likely form type for particular slope sections. Further implications of these two hypotheses are that there may be either a fundamental slope control on peat landslide form, or that there is an intermediate factor, related to slope that affects the forms that result. This might be a material or hydrological characteristic distinct to the ranges of slope and altitudes considered in section 3.2.3. Subsequent work should attempt to standardise the measurement of both deposit and scar form. All deposit types should be logged in both distribution and nature (e.g. solid, slurry). It will then be possible to relate deposit size and form to position in the debris trail, and potentially to mode (rolling, sliding) and relative velocity of transport.

Consideration of slide and burst mechanism focused on summary assessments of material characteristics, and location of the failure plane (section 3.2.4). Only stratigraphic data was available in enough detail to generate hypotheses, as follow:

ix) Peat slides occur on hillslopes characterised by distinctly layered profiles.

x) Bog bursts occur on hillslopes characterised by simplistic profiles, dominated by two major layers, the lower of which is highly humified or amorphous, and the upper of which is more fibrous.

These hypotheses imply distinctive material characteristics for slides and bursts, that may be easily tested with basic stratigraphic survey. However, they do not explain how the materials are responsible for regulating the response of the peat mass to stress. This must be further investigated using standard geotechnical approaches.

xi) Peat failures involving the detachment *and* transport of material underlying the peat mass do not initiate by the same mechanism as bog bursts.

The location of the failure plane, as revealed by the exposed material cannot be used as a differentiating factor on its own, as peat slides show failure planes both in the peat and substrate. However, bog bursts are always described as failing within the peat mass, and hypothesis xi) reflects this. Evidence for the location of the shear plane should be collected at all surveyed sites.

xii) Peat failures associated with drainage lines will show form characteristics inherited from them.

This statement supports the idea that peat failures are to some extent determined in form by the presence of drainage lines either feeding them, or occupying part of the transported peat mass. The material characteristics of the waterlogged drainage lines may be responsible for this. In the case of linear downslope drainage, this may lead to inherited elongate scar forms.

The representation of recovery in the database was limited to broad presence/absence assessments of factors promoting vegetative recovery and landform stability, and the factors impeding these (section 3.2.5). Slides and bursts were shown to retain differing quantities of peat post-failure. These differing baseline conditions would be likely to affect recovery rate, and hence influence estimation of their true populations from field evidence. Bog bursts would be expected to recover at a far greater rate than peat slides. Hypotheses specific to recovery are based more upon supposition of sequences of recovery than temporally defined patterns, and are as follows:

xiii) sites at which recovery is taking place will exhibit distinct patterns and sequences of plant succession with increasing age, and across sites of similar initial conditions.

xiv) sites at which recovery is taking place will be characterised by surface mineral conditions that represent a departure from substrate conditions towards more plant hospitable soil (or peat) cover.

xv) sites at which recovery is taking place will be characterised by an absence of geomorphic activity.

xvi) a bog burst site under similar climatic conditions and topographic setting to a nearby peat slide of the same age, would be expected to exhibit recovery characteristics and rates far in excess of those shown by the peat slide.

The research implications of these statements are twofold. Firstly, either a long-term monitoring approach, or a spectrum of sites of differing age is required to quantify rates of recovery. Secondly, this sample of sites must comprise either peat slides *or* bog bursts, because the baseline conditions for recovery differ too greatly for recovery sequences to be directly comparable. Hence, the use of the North Pennine regional set of peat slide failures is justified.

3.4 Chapter summary

This chapter has provided a quantitative basis for a distinction between peat slides and bog bursts, following the themes discussed in Chapter 2. It has examined their spatial characteristics and temporal distribution from the catchment to the site scale. Key differences between slides and bursts have been identified, and summarised in the form of speculative hypotheses. Although the database has some limitations, mainly related to population size, and to a lesser extent, content, it acts as a powerful analytical synthesis of over 300 years of research into peat mass movements. The potential for further development is considerable, but beyond the scope of this thesis. Subsequent chapters take the hypotheses relevant to peat slides as starting points for further empirical research.

4. MORPHOLOGICAL CHARACTERISTICS OF PEAT SLIDES

4.0 Introduction

It has been suggested that peat slides display a characteristic suite of morphological features that may distinguish them from other mass movement types. This chapter summarises field surveys that support this assertion. These are based upon detailed geomorphological assessment of 14 North Pennine peat slides, supplemented by interpretation of aerial and ground photography. Information from the database in Chapter 3 is used for comparative purposes. The chapter begins with a statement of objectives, which attend to the research gaps described and evaluated in the previous two chapters. The chapter objectives follow from the specific hypotheses identified in Chapter 3 (section 3.3). The aims are:

i) to establish whether there is a form-based justification for a two-fold division of solid peat deposit into blocks and rafts;

ii) to establish whether this solid deposit exhibits a characteristic form, which may be used as an indicator of mechanisms of initiation, transport and definition;

iii) to establish the significance and character of peat slurry as a form of deposit;

iv) to characterise the nature of non-deposit morphological evidence as a basis for definition of peat slides in the field; and,

v) to determine the range of relief that characterises the North Pennine peat slide population, and relate this to the wider peat failure population discussed in Chapter 3, section 3.2.1.

Field and desk-based methodologies are outlined and justified. An introduction to the North Pennine peat slide population follows, and detailed analysis of landforms associated with both scar and deposit elements is presented. Morphological criteria for the definition of peat slides in both field and laboratory environments are suggested. Within the context of this chapter, description of morphological conditions is restricted to dimensional aspects of form, both for individual morphological units (e.g. blocks) and for collective aspects of scar and deposit (i.e. morphometry). The implications of the spatial distribution of form attributes (e.g. block size, location of tension cracks) are considered in the following chapter, which uses depositional evidence to infer the dynamics of sediment transport at peat slide sites. Morphology and sediment dynamics are synthesised as a morphological-conceptual model, with inferred processes used to explain the juxtaposition of features described in this chapter.

4.1 Methodology

Characterisation of peat mass movement morphology has concentrated on field mapping and hillslope transects (Mitchell, 1938; Wilson and Hegarty, 1993; Selkirk, 1996). Where aerial photographs have been available, some authors have used them to produce maps of deposit elements, such as the crescentic rafts in bog bursts (Feldmeyer-Christe, 1995). Approaches within the published peat slide literature have been patchy and limited in extent. Table 4.1 shows the methods used in the most comprehensive studies of peat failures. Those that focus on slope profiles and estimates of scar area, base these on measurements of maximum scar length, width and depth. Geomorphological mapping, frequently utilised in other studies of mass movement (e.g. Brunsden and Jones, 1972; Crozier, 1986; Harris and Lewkowicz, 1993) is rarely used in peat slide studies, other than in the examples cited previously. Deposit mapping and measurement of tension features has been undertaken, but description tends to be basic. More sophisticated aerial photograph interpretation has been used by Feldmeyer-Christe and Mulhauser (1994) in conjunction with remote sensing techniques to discriminate deposit types on the basis of moisture content. There have been no attempts to date to examine sediment loss in the aftermath of failure.

Landslide morphology and morphometry is considered using three techniques - geomorphological mapping, measurement and description of individual form features, and morphometric assessment of scar, deposit, and hillslope form. A framework for these methods, and subsequent analysis is shown in Figure 4.1. The different methods employed are applicable at various scales, from hillslope to feature, but all contribute to an understanding of peat slide form. The following sections describe the specific methodology.

4.1.1 Geomorphological mapping

Table 4.2 shows detail of aerial and ground photography available for each of the

Table 4.1. Methods used in the study of peat mass movements

Topographic Setting			Morphology and Morphometry				Sediment Budgeting		
Down-slope profiles	Cross-slope profiles	Contour survey	Deposit measurement	Tension feature measurement	Geomorphological mapping	Aerial photograph interpretation	Quantification of scar area	Estimate of deposit volume	Authors
									Acreman (1991)
✓							✓	✓	Carling (1986)
			✓				✓	✓	Crisp *et al.* (1964)
					✓		✓	✓	Dykes and Kirk (2001)
									Johnson (1992)
✓	✓							✓	Large (1991)
✓			✓		✓		✓		Mitchell (1938)
					✓		✓		Selkirk (1996)
✓					✓				Tomlinson and Gardiner (1982)
								✓	Veyret and Coque-Delhuille (1993)
✓			✓		✓		✓	✓	Wilson and Hegarty (1993)
✓			✓		✓	✓			* Feldmeyer-Christe (1995)
✓	✓				✓			✓	* Delap *et al.* (1932)
✓	✓			✓	✓				* Praeger (1987)
✓	✓	✓					✓	✓	* Alexander *et al.* (1986)

* bog burst morphology mapping

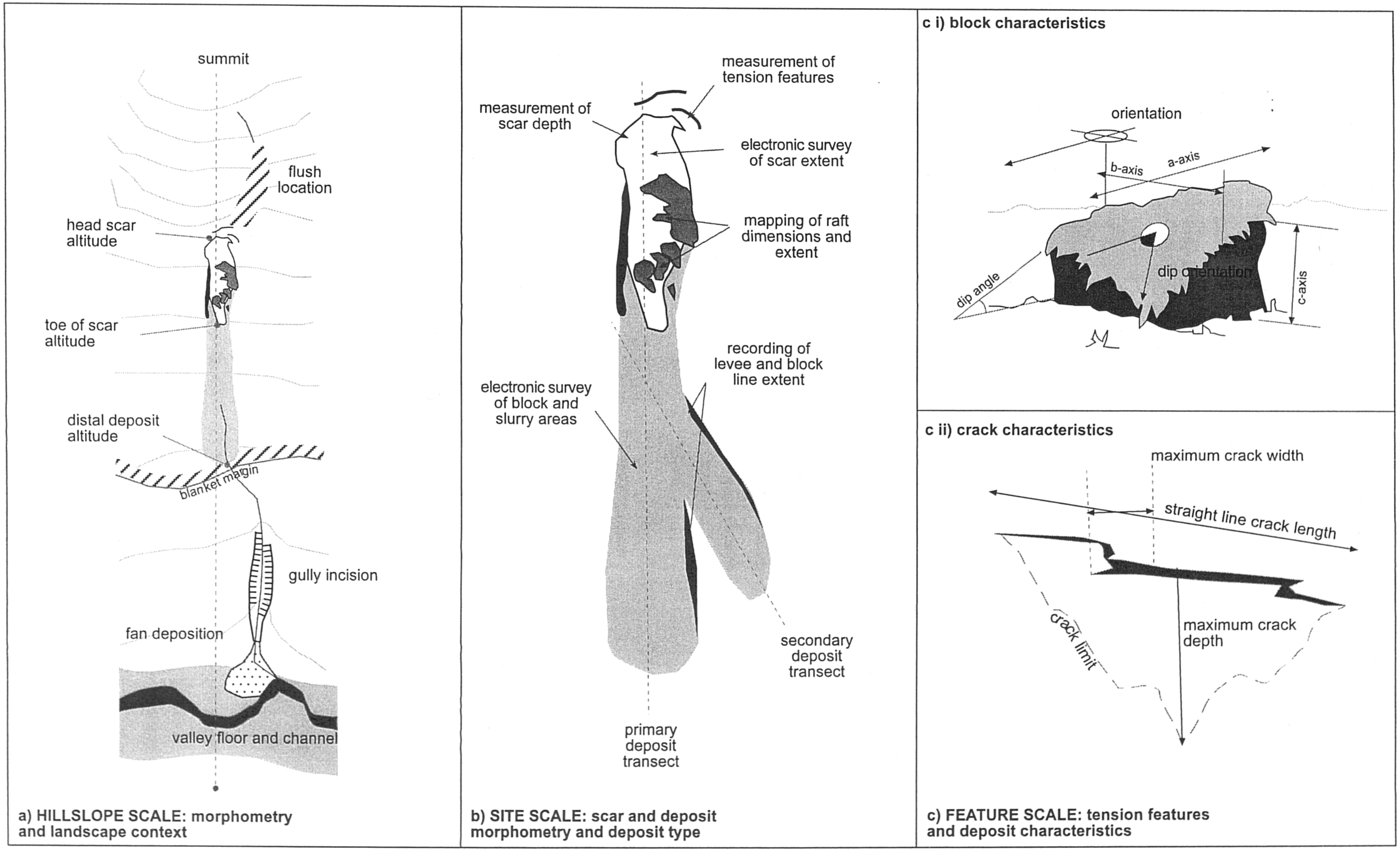


Figure 4.1. Methodological framework for peat slide morphology and landscape mapping

North Pennine slides. Aerial photographs of each slide were obtained where possible. Ideally, colour images at a 1:10 000 scale were used. In addition, ground photography was available for some sites.

Other than at the relatively recent Coldcleugh Head failure at Nenthead, aerial photograph coverage was available for all slides. 1:25 000 scale air photos were of variable quality, but both black and white and colour photography at 1:10 000 scale provided detailed coverage of most slide sites. Fortuitously, those covering the cluster of slides at Noon Hill possessed great clarity of image. Scanning and simple image processing (contrast and brightness) enabled individual blocks (down to a few metres in dimensions) to be identified. Grips, scar margins and the larger surface tears were also visible on these photographs.

In addition to the photographs noted above, oblique aerial photography was obtained from low-level flights over the North Pennines in the spring of 2000. This enabled further evaluation of the failure sites and definition of morphological components. For example, rill extent, other than by field survey is picked out most clearly on the oblique photographs of the Benty Hill failure rather than the overhead aerial photograph. Ground based photographs taken in the immediate aftermath of failure also provide valuable information. Photographs were borrowed by kind permission of J. Adamson, T. Crisp and I. Forbes.

For the purpose of field mapping, both overhead and oblique aerial photographs were laminated, and then annotated in the field with key morphological features not necessarily visible in high level photography. Features included the presence of debris (rafts, blocks and slurry), cracks and tears, ridges and levees, the location of the scar margin, key drainage lines that had developed on the scar, the location of scar proximal drainage features (pipes, streams, grips, flushes) and the location of material samples.

Pre-failure aerial photographs were also analysed for evidence of prior drainage lines and compared with the position of each slide scar. Connecting systems both upslope (e.g. flushlines) and downslope (e.g. gullies) were mapped. This was attempted for the Noon Hill slides, and at Feldon Burn and Hart Hope.

Table 4.2. Aerial photograph information for North Pennine peat slides.

Slide name	Date of failure	Scale	Colour/BW	Date of photograph	Lag time failure/photo	Ground photograph availability	Pre-failure air photo availability	Period between pre-failure photo and failure
Benty Hill	??/01/92	1:25 000	Colour	12/11/92	10 months	none available	none available	n/a
Coldcleugh Head	??/??/98	n/a	n/a	n/a	n/a	none available	none available	n/a
Dow Crag	18/06/30	1:25 000	Colour	21/08/98	68 years	none available	none available	n/a
Feldon Burn	24/08/90	1:10 000	Colour	10/09/97	7 years	none available	available	* days
Hart Hope	02/02/95	1:10 000	Colour	06/08/95	7 months	available *	available	45 years
Iron Band	??/??/64	1:25 000	Colour	21/08/98	34 years	available **	none available	n/a
Langdon Beck	??/??/61	1:10 000	BW	08/07/89	28 years	none available	none available	n/a
Langdon Head	17/07/83	1:10 000	BW	08/07/89	6 years	none available	available	32 years
Meldon Hill East	06/07/63	1:10 000	BW	08/07/89	26 years	available **	none available	n/a
Meldon Hill West	06/07/63	1:10 000	BW	08/07/89	26 years	none available	none available	n/a
Middlehope	17/07/83	1:10 000	Colour	26/06/95	12 years	none available	none available	n/a
Nein Head 2	17/07/83	1:10 000	Colour	18/05/92	9 years	available ***	available	32 years
Nein Head 3	17/07/83	1:10 000	Colour	18/05/92	9 years	available ***	available	32 years
West Grain	17/07/83	1:10 000	Colour	18/05/92	9 years	none available	available	32 years

* courtesy of J.Adamson
** courtesy of T. Crisp
*** courtesy of I. Forbes
?? Denotes unknown date

4.1.2 Deposit characteristics

Given the range of deposit types and distribution, detailed deposit mapping was undertaken at each slide site. This involved the surveying of the spatial distribution of blocks at each site. Form attributes were noted for each surveyed block (Figure 4.1). These block attributes were chosen to reflect deposit size and shape, hillslope orientation, angle and orientation of top surface dip and degree of smoothing in transport (Table 4.3). Maximum block depth (c-axis), as opposed to mean depth was measured because it could be consistently identified in the field, and was most representative of initial peat depth. Maximum and minimum elevation of the block top plane over the peat blanket were used to determine block dip. The dominant tilt direction of the larger peat masses, usually found closer to the scar itself, was also noted. The degree of smoothing was determined on the basis of edge characteristics of each block:

i) **Angular:** sharply defined apices, clearly polygonal, no disruption of marginal peat faces by secondary weathering and erosion;

ii) **Sub-angular:** defined apices, mostly polygonal, slight marginal weathering only;

iii) **Sub-rounded:** muted apices, extensively collapsed or weathered margins, overhanging turf top-surface;

iv) **Rounded:** no sidewall visible, collapsed margins and connection of turf mat with peat surface.

Gross block form attributes (a-, b- and c-axes) are considered to be primarily representative of shaping by abrasion during transport. The degree of smoothing is more likely to be a function of post-depositional weathering. Assessment of the latter provides a means of assessing the validity of form measurements at sites of differing age.

On the basis of initial estimates, the largest sites contained well in excess of 500 blocks (e.g. Nein Head 2 and Hart Hope), and this necessitated some degree of sub-sampling. At sites estimated as having over 500 blocks, approximately 1 in 4 blocks were surveyed. At sites with less than 500 blocks, a ratio of 1:3 were surveyed, and for

Table 4.3. Criteria for measurement of block attributes.

Attribute	Method	Criteria	Purpose
a axis	tape measure	maximum slope-parallel block length	size and shape, maximum dimensions
b axis	tape measure	maximum block width orthogonal to a axis	size and shape
c axis	tape measure	maximum block depth perpendicular to vegetated surface	size and shape
a axis orientation	compass	upslope end to downslope end axis orientation	flow alignment
dip	clinometer	maximum block elevation (a.b.s.) to minimum block elevation (a.b.s.)	tendency to backtilt
dip orientation	compass	orientation from maximum (a.b.s.) to minimum elevation (a.b.s.)	tendency to backtilt
roundness	qualitative assessment	by 'eye' judgement	shape

Table 4.4. General detail for North Pennine peat slides.

Slide name	Date of failure	Grid Reference	Altitude of scar head (m)	Slope-channel coupled	First published by
Benty Hill	??/01/92	NY 677 425	545	y	unpublished
Coldcleugh Head	??/??/98	NY 797 425	615	n	unpublished
Dow Crag	18/06/30	NY 839182	545	y	Hudleston, 1930
Feldon Burn	24/08/90	NY 999 454	465	y	Johnson, 1992
Hart Hope	02/02/95	NY 860327	540	y	Warburton and Higgitt, 1998
Iron Band	??/??/64	NY 829188	530	y	unpublished
Langdon Beck	??/??/61	NY 857346	530	n	unpublished
Langdon Head	17/07/83	NY 848348	580	y	Carling, 1986
Meldon Hill East	06/07/63	NY 771291	670	y	Crisp *et al*, 1964
Meldon Hill West	06/07/63	NY 771291	670	y	Crisp *et al.*, 1964
Middlehope Moor	17/07/83	NY 880425	535	y	unpublished
Nein Head II	17/07/83	NY 849 364	585	y	Carling, 1986
Nein Head III	17/07/83	NY 854 365	600	y	Carling, 1986
West Grain	17/07/83	NY 864 365	580	y	Carling, 1986

sites with less than 100 blocks, 1:2. At sites with very low numbers of blocks (< 20), all blocks were measured. At older sites (1983 and before), many of the features on the ground could not be clearly distinguished from the more widespread hummocky peat terrain. This may lead to a relative bias in sampling towards the larger block features at the older sites.

4.1.3 Measurement of tension features

Tension and compression features were mapped and supplemented with point measurements of crack depth, width and length (Figure 4.1). However, during measurement, a number of difficulties with quantifying the nature of cracks came to light:

i) some cracks were found to be infilled with peat from collapsed sidewalls;

ii) some drier cracks had been occupied by sheep, and probably widened;

iii) many cracks extended for considerable lengths at the surface, but not at depth;

iv) many cracks may have been unrelated to the failure;

In the case of the older sites particularly, drying of the peat surface associated with local drainage would be expected to give rise to surface cracking (Akroyd, 1964; Gilman and Newson, 1980). Consequently, other than for the largest features directly associated with the scar margin, crack measurements were not undertaken extensively at sites other than Nein Head 2 and 3.

4.1.4 Scar, deposit and hillslope morphometry

The dimensions of scar and deposit were calculated using scaled measurements derived from the aerial photographs. Deposit and scar depths were measured in the field as described in the previous sections, and for slide scars as part of the discussion of materials described in Chapter 6. A series of point measurements of peat depth were made along the scar margins at each failure.

Hillslope profiles were constructed along the main failure axis of each slide (see Figure

4.1) using clinometer and tape. Profiles began within 30 m of the headscar, and continued to at least 30 m beyond the furthest terrestrial extent of deposit. Where peat slides exhibited two or more major debris lobes that were likely to have been deposited independently, additional profiles were taken to incorporate them. A point was taken for each perceptible break of slope, or at 30 m intervals, depending upon the complexity of slope form. This approach provides a balance between detail at local points of interest, and efficiency with regard the assessment of the longest features.

In addition, hillslope profiles were constructed from contour information, derived from 1:10 000 scale OS maps at each site. These provided a wider assessment of hillslope form, and of the position of the peat slide with respect to hillslope summits, and the peat blanket margin.

4.2 Results

Table 4.4 shows general details of the North Pennine peat slide sites. A map of failures across the North Pennines has been provided previously (Figure 2.15). Specific aspects of form are considered shortly. The fourteen sites span 68 years, from Dow Crag reported in 1930 (Hudleston, 1930), to Coldcleugh Head in 1998. Four failures occurred in the early 1960s, Meldon Hill East and Meldon Hill West during the same climatic event (Crisp *et al.*, 1964). Iron Band occurred in 1964, and is located on the west flank of the same ridge as Dow Crag. Langdon Beck (1961) is one of five failures occurring around Noon Hill, the other four - Langdon Head, Nein Head 2, Nein Head 3 and West Grain taking place during a summer storm in 1983 (Carling, 1986). The Middlehope (1983) failure also occurred in association with this storm, but several kilometres north-east of Noon Hill. Temporally isolated failures occurred to the west at Benty Hill (1992, pers.comm.), to the north-east at Feldon Burn in 1990 (Johnson, 1992), and again near Noon Hill at Hart Hope in 1995 (Warburton and Higgitt, 1998).

The slides occupy a relatively narrow range of altitudes consistent with occurrence within the blanket peat that characterises the area. A majority of failures are coupled with the local fluvial networks.

There are four reported failures which remain unstudied. Nein Head 1, which occurred at the same time as the other Noon Hill slides, appears to be a peaty-soil failure, rather than a peat slide. It has very small dimensions and is not considered further. Birkbeck Gill was unstudied due to restricted land access, but was reported by Hudleston (1930) as a relatively minor failure. An older Meldon Hill failure was reported by Crisp *et al.* (1964), but insufficient information was available to accurately locate it. Crisp *et al.* (1964) also mention a failure in the Baldersdale locality, but for similar reasons, this could not be located.

The following sections adopt a scaled approach to the description of form at slide sites. At the broadest scale, hillslope form provides a topographic setting for each failure. The distribution of landforms is then considered within each slide using geomorphological mapping. The morphometry of the slide scar and deposit components is then compared with Crozier's (1973) morphometric classification, providing a basis for scale comparison across sites. Finally, the morphological units that comprise scar and deposit are described and summarised.

4.2.1 Topographic and drainage setting

The peat slide scar area is defined as the entire zone from which peat material has been dislocated and excavated. The exposed scar area represents the proportion of scar uncovered by removal of peat (such as blocks, rafts and slurry). The deposit area is defined as the entire area over which peat is deposited, and may incorporate part (or all) of the scar area. The disturbance area represents the entire area over which intact peat has been disturbed by either excavation, deposition, or propagation of cracking and tearing. A schematic representation of these definitions is shown in Figure 4.2.

Figure 4.3 illustrates hillslope profiles from above the slide scar heads to the lower deposit limits for each peat slide in the North Pennines. Local irregularities relate to significant peat deposits (e.g. Benty Hill, Feldon Burn). These profiles may be compared with Figure 4.4, which illustrates the altitudinal limits of the hills, scars and blanket peat for each failure. The position of the peat margin at each slide is estimated from a combination of field evidence and aerial photograph interpretation. This is used in combination with contours on local OS maps to plot the altitude of the blanket margins. Table 4.5 notes the height fall and distance relative to the summits of each scar head, the dominant slope form, and the hillslope position of each failure, be it planar valley side, gully head or otherwise. Upper, lower and mean slope angle of each failure scar are also shown.

At the hillslope scale, topographic setting is variable from site to site. Failures occur over a variety of convexities, concavities and rectilinear slopes. The scar slope forms

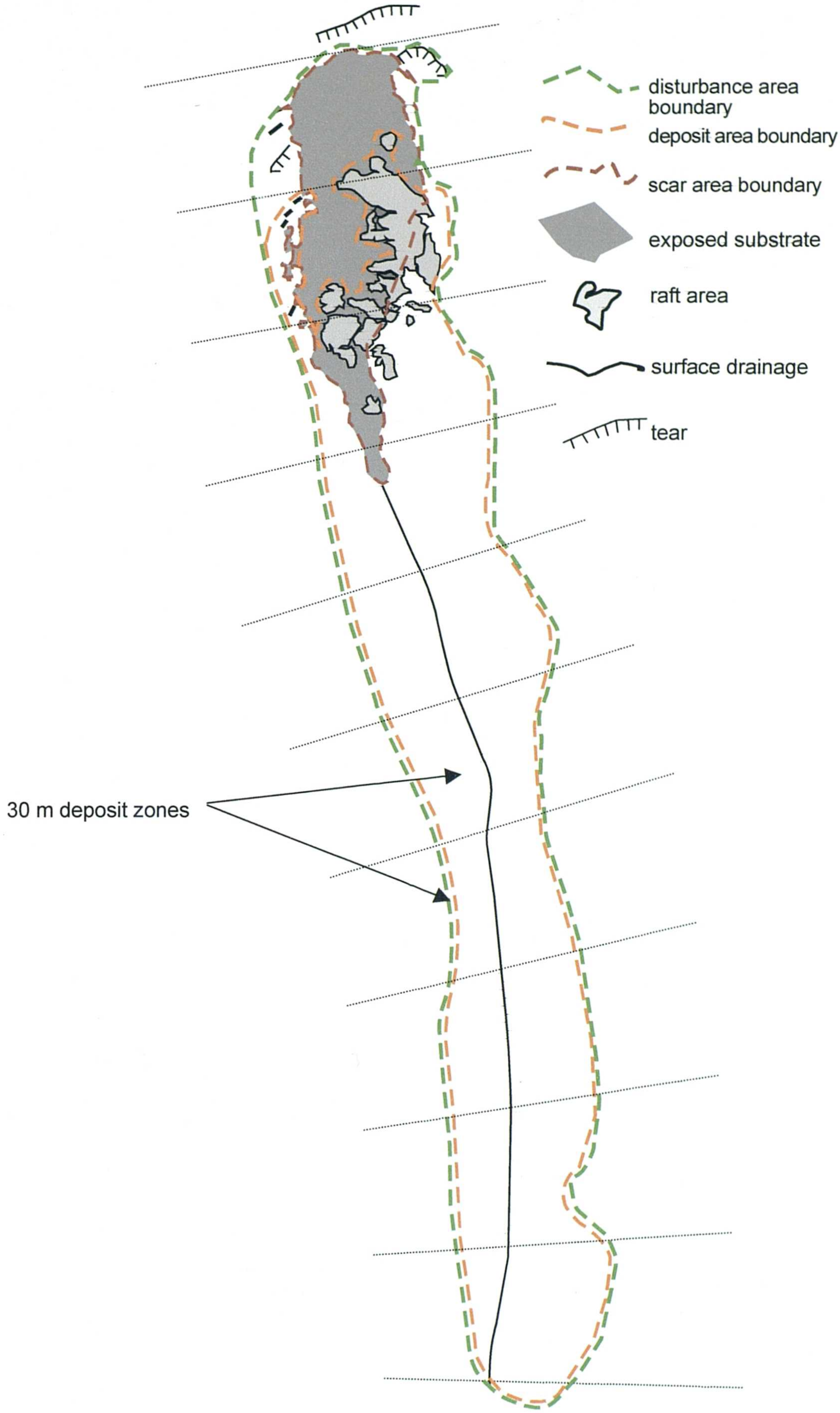


Figure 4.2. Schematic definition of peat slide zones used in event sediment budgets

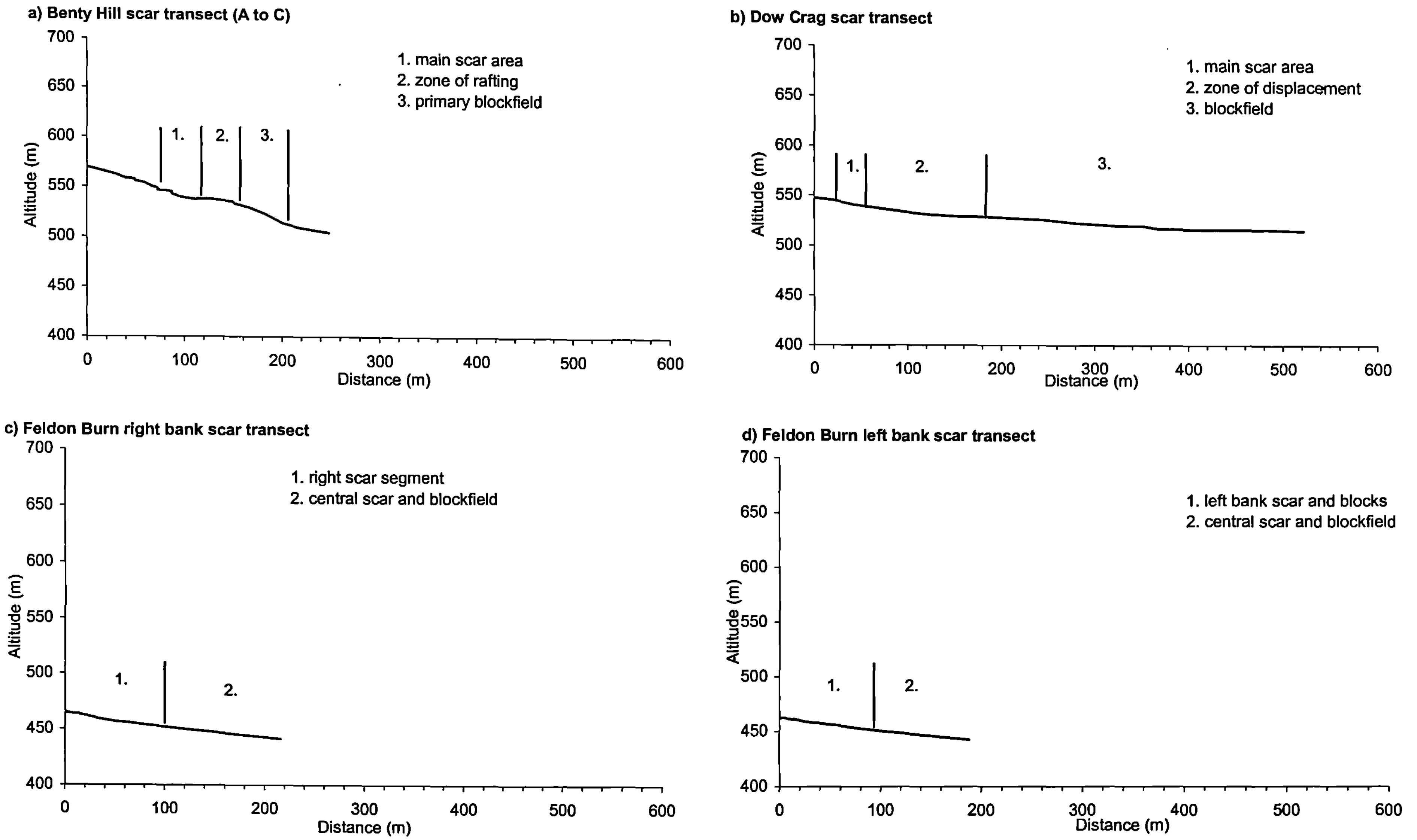
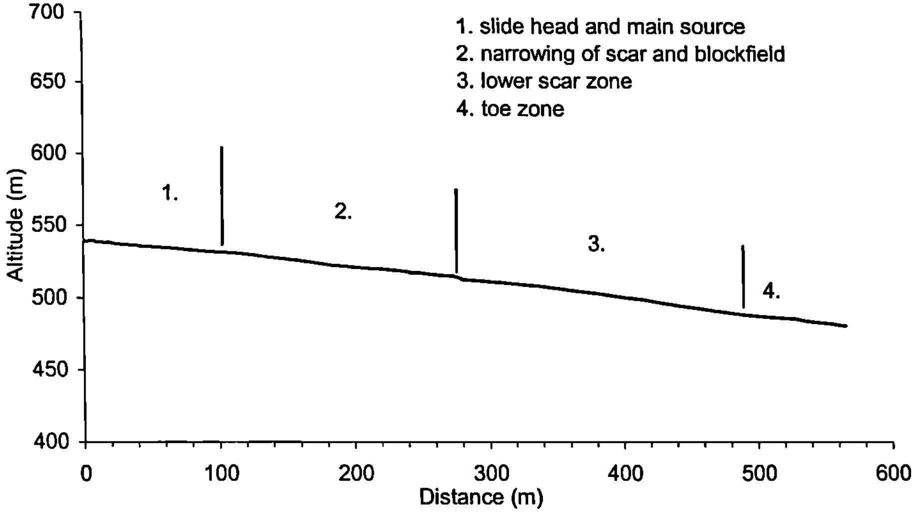
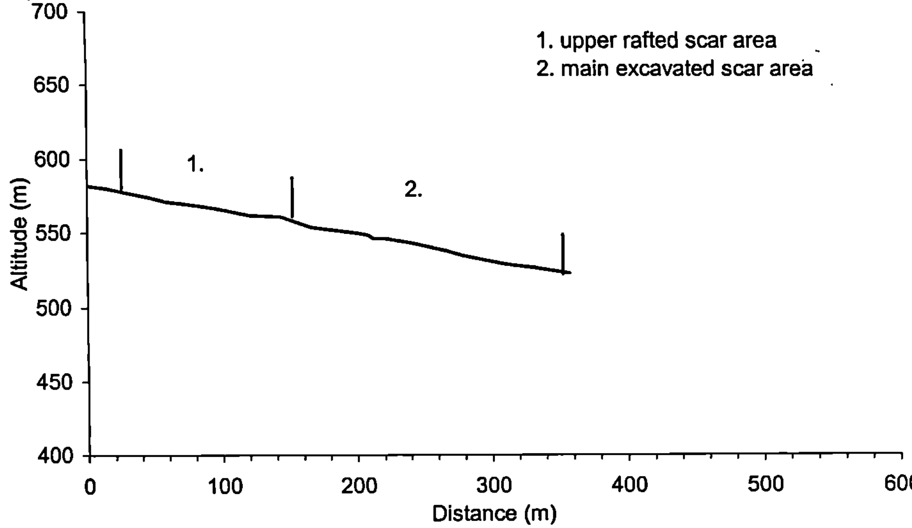


Figure 4.3. Hillslope profiles for North Pennine peat slides

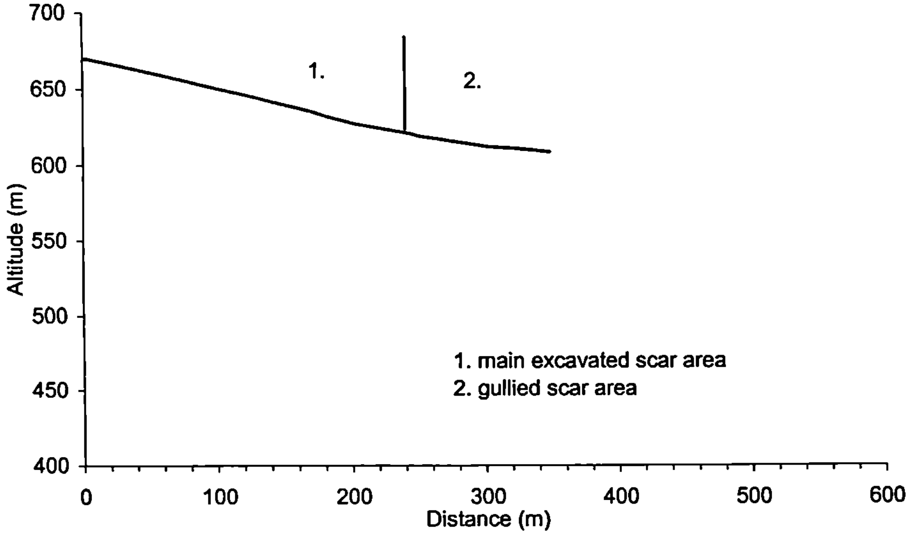
e) Hart Hope slope transect



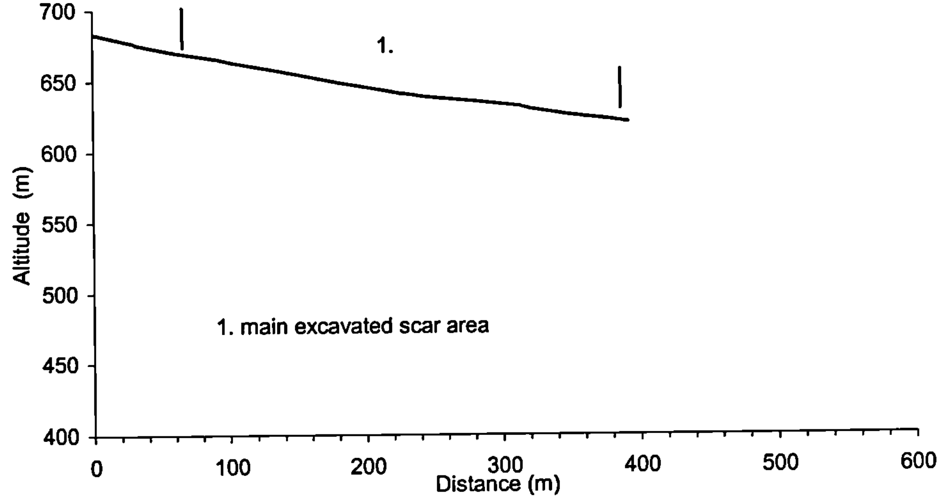
f) Langdon Head transect



g) Meldon Hill East scar transect



h) Meldon Hill West scar transect



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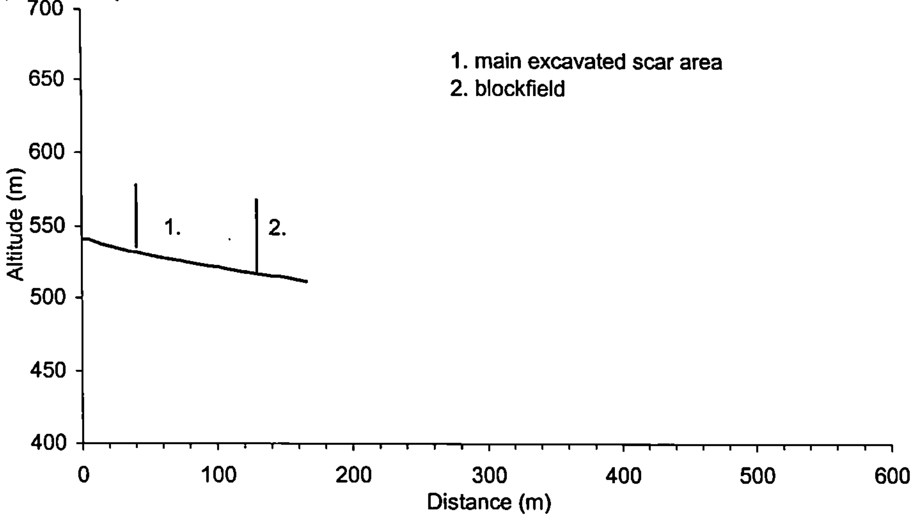
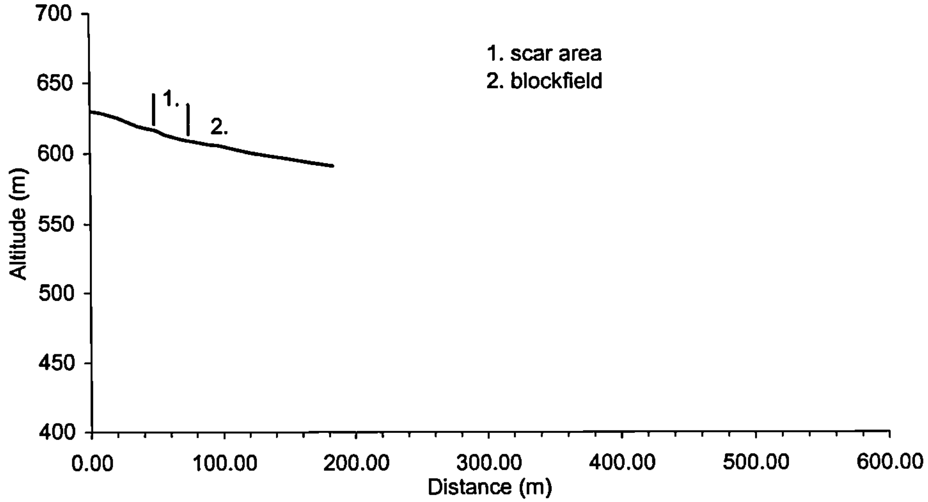
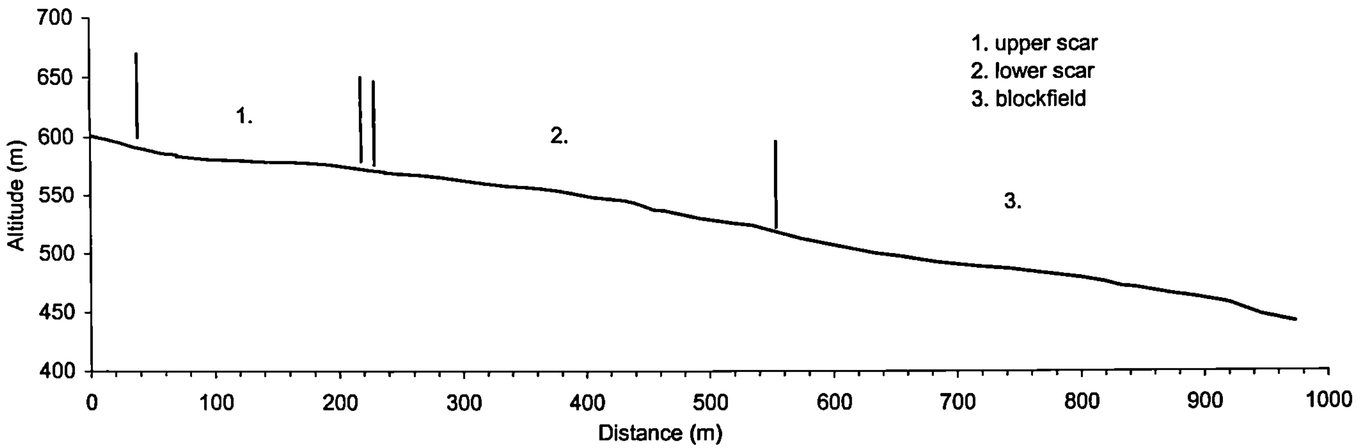
i) Middlehope scar transect



j) Coldcleugh head scar transect



k) Nein Head 2 scar transect



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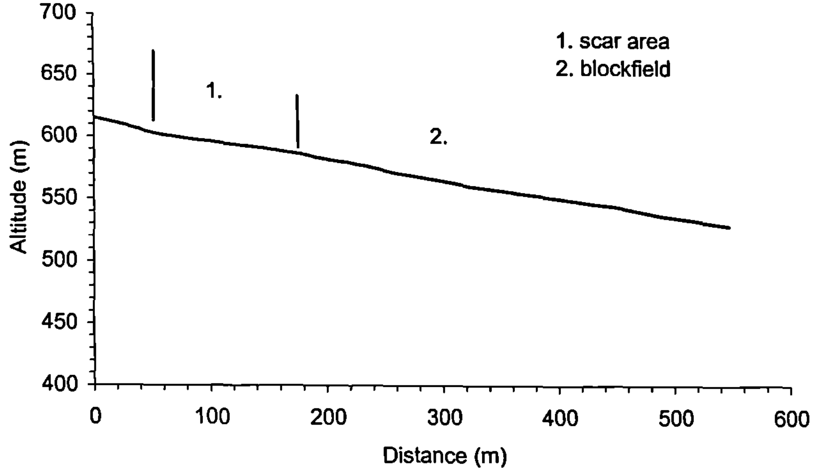
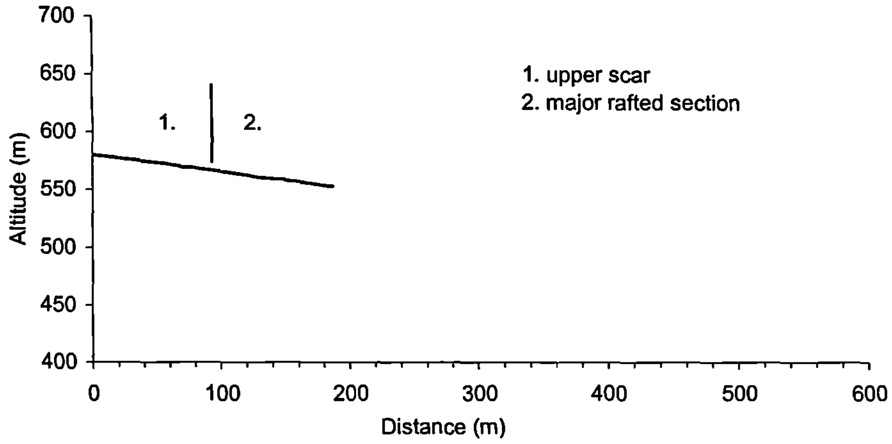
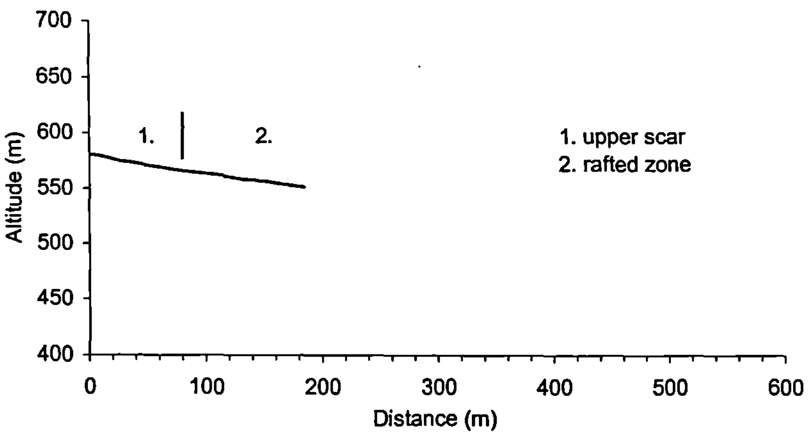
l) Nein Head 3 scar transect



m) West Grain right bank scar transect



n) West Grain left bank scar transect



o) Iron Band scar transect

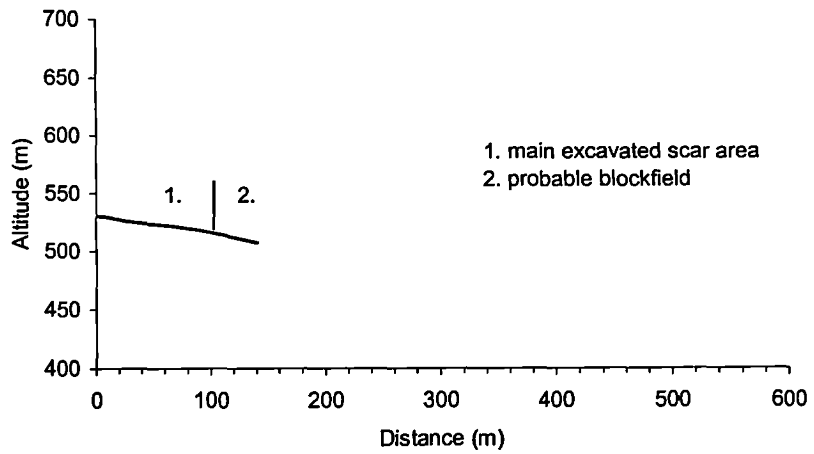


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Figure 4.4. Altitude plots of summit, valley, scar limit and margin

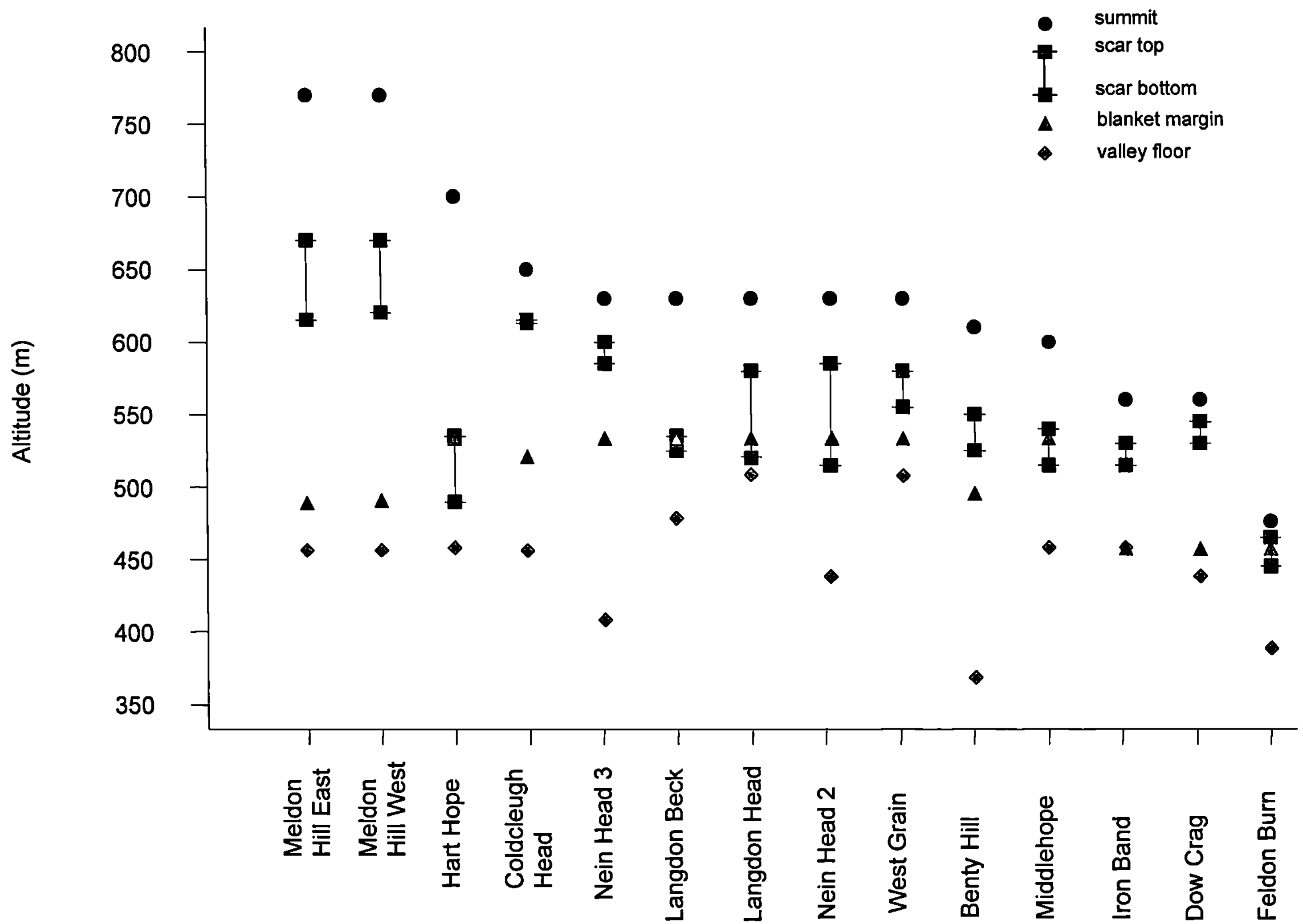


Table 4.5. Hillslope setting and scar and deposit morphometry for North Pennine peat slides.

Slide name	Scar long profile form	Hillslope long profile form	Catchment position	Head altitude (m)	Toe altitude (m)	Horizontal distance: summit to head (m)	Vertical distance: summit to head (m)	Upper slope angle (deg)	Lower slope angle (deg)	Mean slope angle (deg)
Benty Hill	steeped rectilinear	convex	side slope	550	525	575	60	19.5	28.5	24.0
Coldcleugh Head	convexo-concave	concavo-convex	side slope	615	613	180	35	56.3	19.6	37.9
Dow Crag	concave	concavo-convex	head slope	545	530	250	15	6.2	3.2	4.7
Feldon Burn	concave	rectilinear	head slope	465	445	150	11	12.6	7.8	10.2
Hart Hope	rectilinear	convex	side slope	535	490	1900	165	5.9	8.3	7.1
Iron Band	*concavo-convex*	convexo-concave	side slope	530	515	385	30	11.0	16.7	13.8
Langdon Beck	convex	convex	side slope	535	525	890	95	13.6	10.9	12.2
Langdon Head	steeped rectilinear	convex	head slope	580	520	512	50	12.6	12.6	12.6
Meldon Hill East	concave	convexo-concave	side slope	670	615	687	100	17.0	24.1	20.6
Meldon Hill West	concave	convexo-concave	side slope	670	620	687	100	16.3	12.7	14.5
Middlehope	rectilinear	convex	head slope	540	515	680	60	19.2	28.4	23.8
Nein Head II	concavo-convex	convexo-concave	side slope	585	515	340	45	4.5	9.9	7.2
Nein Head III	rectilinear	convex	side slope	600	585	225	30	11.0	11.0	11.0
West Grain	rectilinear	convex	head slope	580	555	320	50	11.0	11.0	11.0

that result are also complex, reflecting the morphometry of the substrate surface underlying the former peat body. Information as to slope extent and steepness is best considered in terms of the values in Table 4.5. Scar areas can be divided into those which occur over concavities, those over convexities, and those on rectilinear slopes. The scar areas of Benty Hill (Figure 4.3a) and Langdon Head (Figure 4.3f) exhibit stepped rectilinear profiles, characterised by local stepped descents. Slopes range between 19.5° and 28.5° in the Benty Hill sequence, while the Langdon Head failure shows more gentle slopes averaging around 12°. Hart Hope, Middlehope, Nein Head 3 and West Grain occur on simple rectilinear slopes. Slope angles range from shallow slopes at Hart Hope (7.1°; Figure 4.3e), to steeper slopes at Middlehope (19.5° for all but the lowest portion of the slope; Figure 4.3i). The Dow Crag, Coldcleugh Head, Feldon Burn and Meldon Hill failures occur within concavities, though the deposits of the latter finally runout in steepening gully systems. Slope angles are shallow at Dow Crag (6° to 3°; Figure 4.3b) and steeper at Meldon Hill (16° over the main scar, steepening to 24° in the gullies; Figures 4.3g and h). Iron Band (Figure 4.3f) and Nein Head 2 (Figure 4.3k) have scars that initiate in slight concavities, but which extend over convex slope forms (11° to 17° at Iron Band; 4.5° to 10° at Nein Head 2). There is no clear tendency towards slope forms of either a convex or concave profile, as suggested in Chapter 3. The data does partially support the assertion that failures occurring over slopes greater than 15° occur on convex slopes (e.g. Benty Hill, Middlehope) and under 15° on concave slopes (e.g. Feldon Burn, Dow Crag). However, there are a number of failures which do not correspond to this premise. It is not possible on the basis of this sub-sample of slides to define hillslope profiles characteristic of peat slides. Scar and hillslope long profiles may be of significance in the runout of deposit, and are discussed further in Chapter 5.

Coupling of the slide scars and deposit is rarely dependent upon the hillslope position of each failure. Only Coldcleugh Head and Langdon Beck are not coupled to local fluvial networks. The scar and deposit extents of the other failures are significant enough that even slides initiating near hillslope summits (e.g. Nein Head 3, Nein Head 2, Iron Band) are coupled. Slides at lower altitude generally occur over lower relief, and often incorporate more established drainage lines closer to higher order fluvial systems (e.g. Dow Crag, Feldon Burn, Hart Hope). The scars of both Langdon Head and Hart Hope are directly coupled with tributaries of the Tees. Conversely, the Meldon Hill failures occur significantly below their common hillslope summit, but are coupled through a considerable degree of gully extension on Meldon Hill.

Figure 4.5 utilises pre-failure aerial photography to elucidate drainage conditions in the peat now occupying slide scars. Examples are shown for Nein Head 2, Nein Head 3 and Feldon Burn. It is possible to make sensible estimates of field moisture conditions on the basis of tone alone (Way, 1972).

Figure 4.5a shows an enlargement of the Nein Head 3 site taken in July 1951, 32 years prior to failure. Major morphological elements (scar, blocks, drainage lines) are shown on the right hand side, while inferred soakways are shown on the left. Field calibration of ground vegetation (at Nein Head 2, adjacent to the scar area) suggests that the darker features (on aerial photographs in general) are wetter in intact blanket bog, and that these are dominated by *Sphagnum* and *Polytrichum*. The juxtaposition of the darker areas downslope of the drainage inputs from the torn margin upslope (1), support this idea. If this is the case, it appears that the major displaced mass at Nein Head 3 was transported from within wetter surrounding flushy peat. If this is the case, it is the drier peat that has been lost. There does not appear to have been any significant drainage feature within the peat displaced by the failure, and indeed it appears that the surface soakways bypass the failed area to feed the stream downslope of the current scar.

Figure 4.5b shows a more managed blanket peat surface at Nein Head 2, where grips still active today are present in 1951. Again, darker (and wetter) peat is visible in several downslope oriented surface soakways, and in a broad belt beneath a torn peat edge fed by at least four immature gullies (2). Only those surface features in the immediate vicinity of the slide scar have been highlighted. The excavated bog surface is mainly the drier mass between soakways. However, the pre-failure peat mass shows a well defined channel feature, emanating from the middle of the scar area, and feeding a central soakway (3). This suggests that this hillslope location acts as a throughput for water entering the site from above.

Finally, Figure 4.5c shows the geomorphological setting at Feldon Burn. Here, the pre-failure photo was taken (fortuitously) three weeks prior to the mass movement (August 1990). This represents the closest documented pre-failure photographic record of a peat slide site to date. The failure is defined on the right hand side photograph, trisected by arcuate grips present prior to movement. However, at this site, ground conditions are quite different to the previous slides. The surface vegetation is heavily disturbed by patchy burning, with the lighter areas (shaded brown) representing burnt heather, and the darkest patches intact heather. Features similar in shape and hillslope orientation to the previously highlighted soakways are visible feeding into the head of the failure and running adjacent to it. The scar itself appears to have

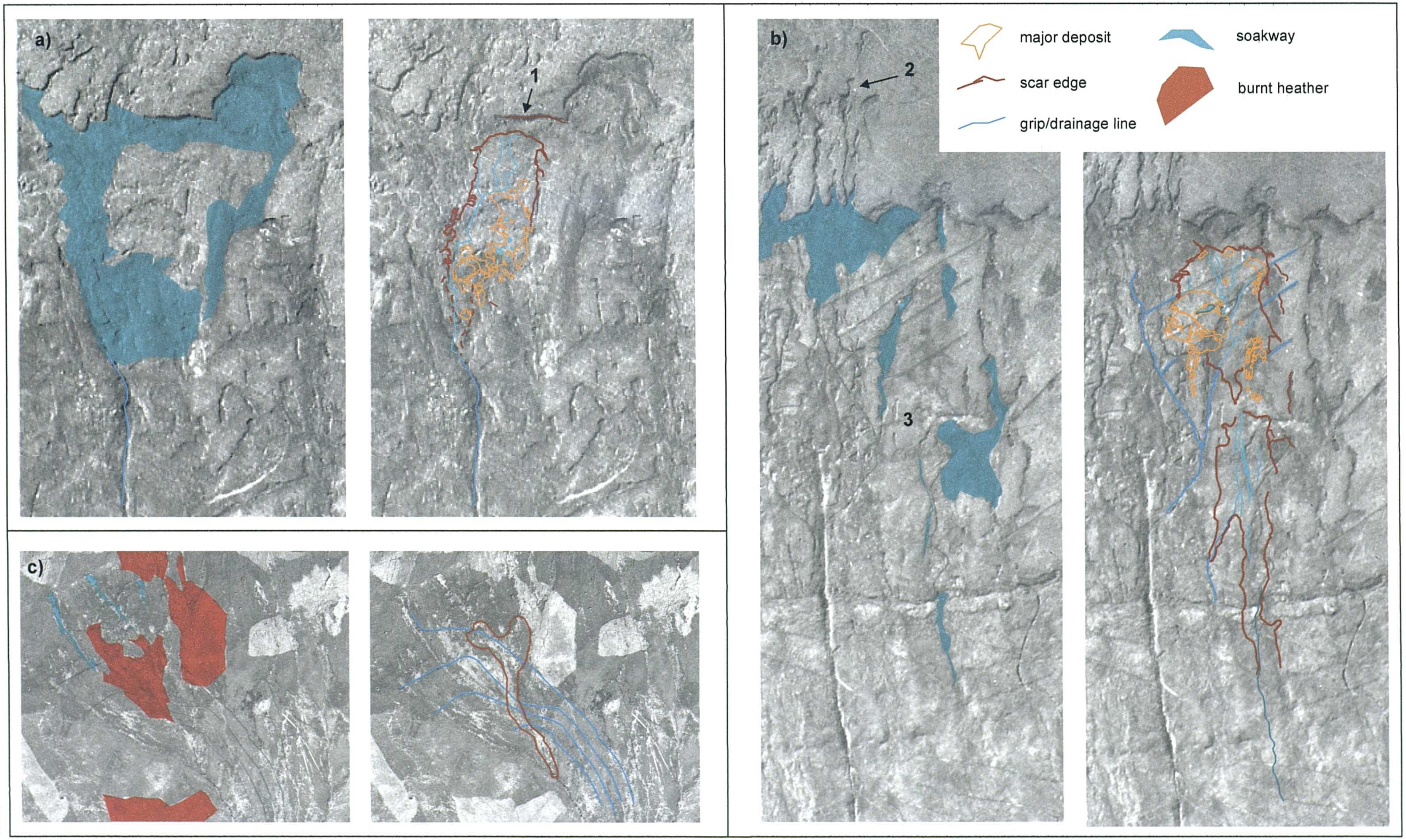


Figure 4.5. Pre-failure conditions for three North Pennine peat slide scars: a) Nein Head 3; b) Nein Head 2; c) Feldon Burn

excavated a mixture of burnt ground and partially recovered heather (speckled). Both the former flushes running through the scar and the latter running adjacently, feed a well defined surface channel that initiates in the terminus of the scar.

Langdon Head, Hart Hope and West Grain were also examined. Hart Hope occurs within established soakways and flushlines, while West Grain occupies no obvious drainage features. There is some local geomorphic activity at the foot of what is now the Langdon Head scar, associated with stream activity in the valley floor.

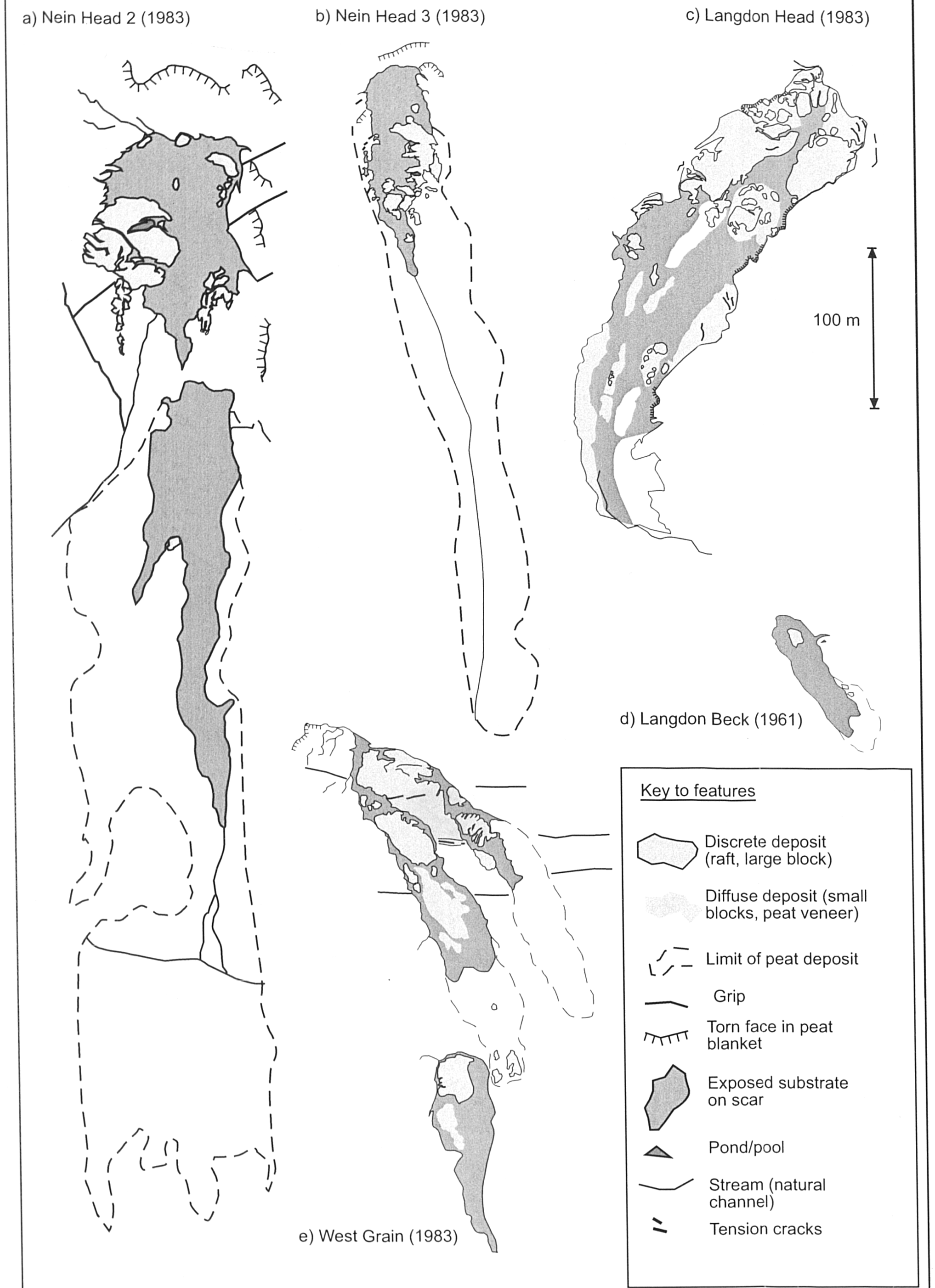
4.2.2 Identification of morphological units using geomorphological maps

Figures 4.6 to 4.8 show geomorphological maps of the full set of North Pennine failures. The scar areas are denoted by the darker grey shading, and concentrations of solid deposit (as rafts or lobes of debris) are shaded lighter grey. The limit to deposition, solid or slurry, is shown by the hashed line. Slides are re-orientated to fit the page. Future reference to slide features in the text should be considered in tandem with these maps, unless a new map has been produced. Figure 4.6 shows the Noon Hill cluster, all but Langdon Beck (1961) occurring during the same storm in July 1983.

Working anticlockwise from the north-east, West Grain (Figure 4.6e) is one of the more complex failures. It consists of three major zones of excavation which lie at the foot of an extensive gully system, and above West Grain (stream) itself. On the upper slope between 585 and 555 m, twin scars with associated lobate deposits lie either side of a slightly disturbed central raft. Dislocation of this central section is shown by a disrupted grip in the middle of the raft, and a compression ridge at its lower limit. Further major rafts occupy much of the scar areas. Peaty debris transported beyond the scar zones has travelled only a short distance relative to some of the other Noon Hill slides. Disruption of the head zone by tearing and cracking appears extensive. The third, lower feature occurred as a gully head failure, in peaty-clay transitional soil. Although spatially and temporally associated with the upper failure, it is not a true peat slide and is not considered in depth in the remainder of this research.

Nein Head 3 (Figure 4.6b) occurs as the northernmost of three slides arranged roughly parallel on the north-western flank of Noon Hill. It is situated beneath a large face in the plateau blanket peat, but is not fed by any significant drainage. The scar area impinges on a small burn that runs into the valley stream of Ireshope Burn. The disturbance area as a whole is dominated by a long runout zone, more than three

Figure 4.5. Geomorphological maps of the Noon Hill peat slides



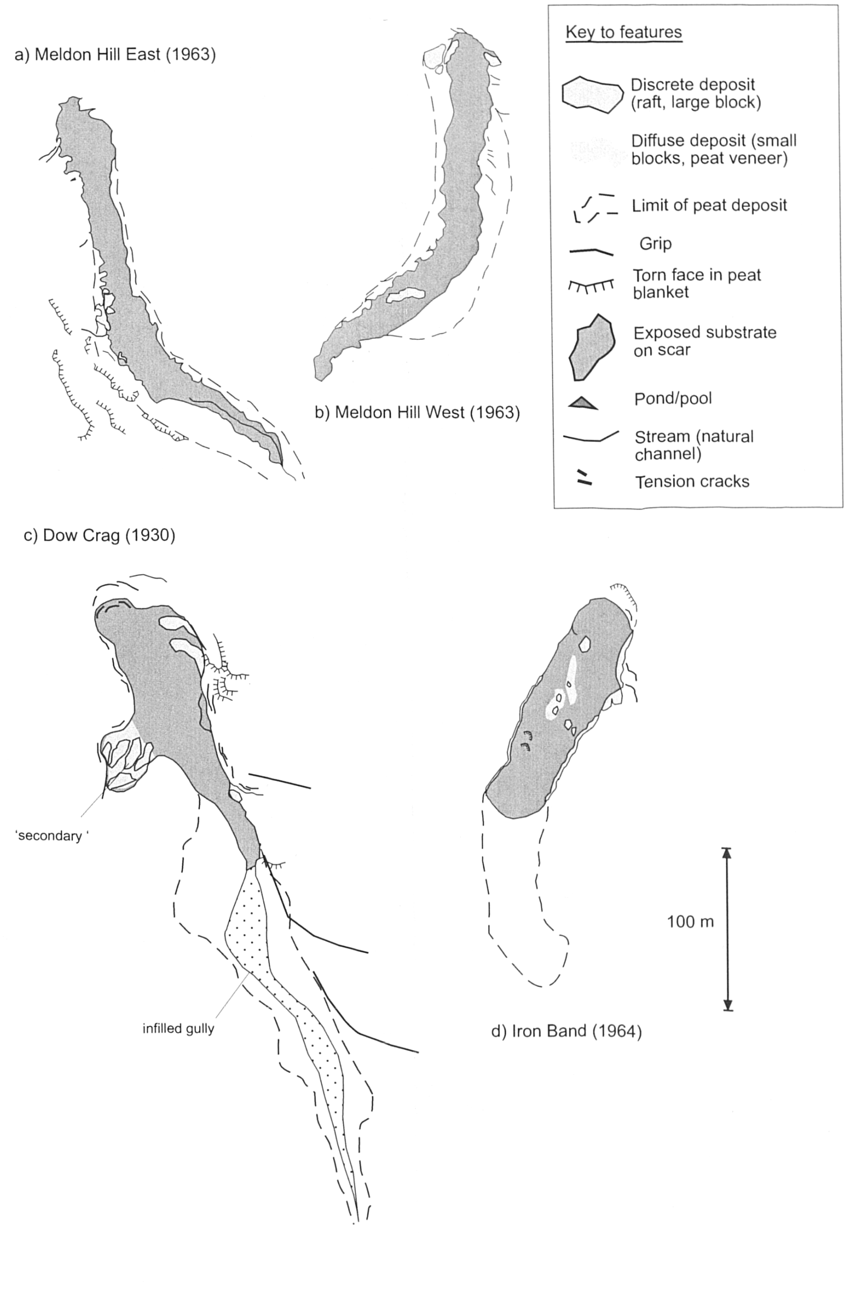


Figure 4.6. Geomorphological maps of the Meldon Hill and Stainmore peat slides

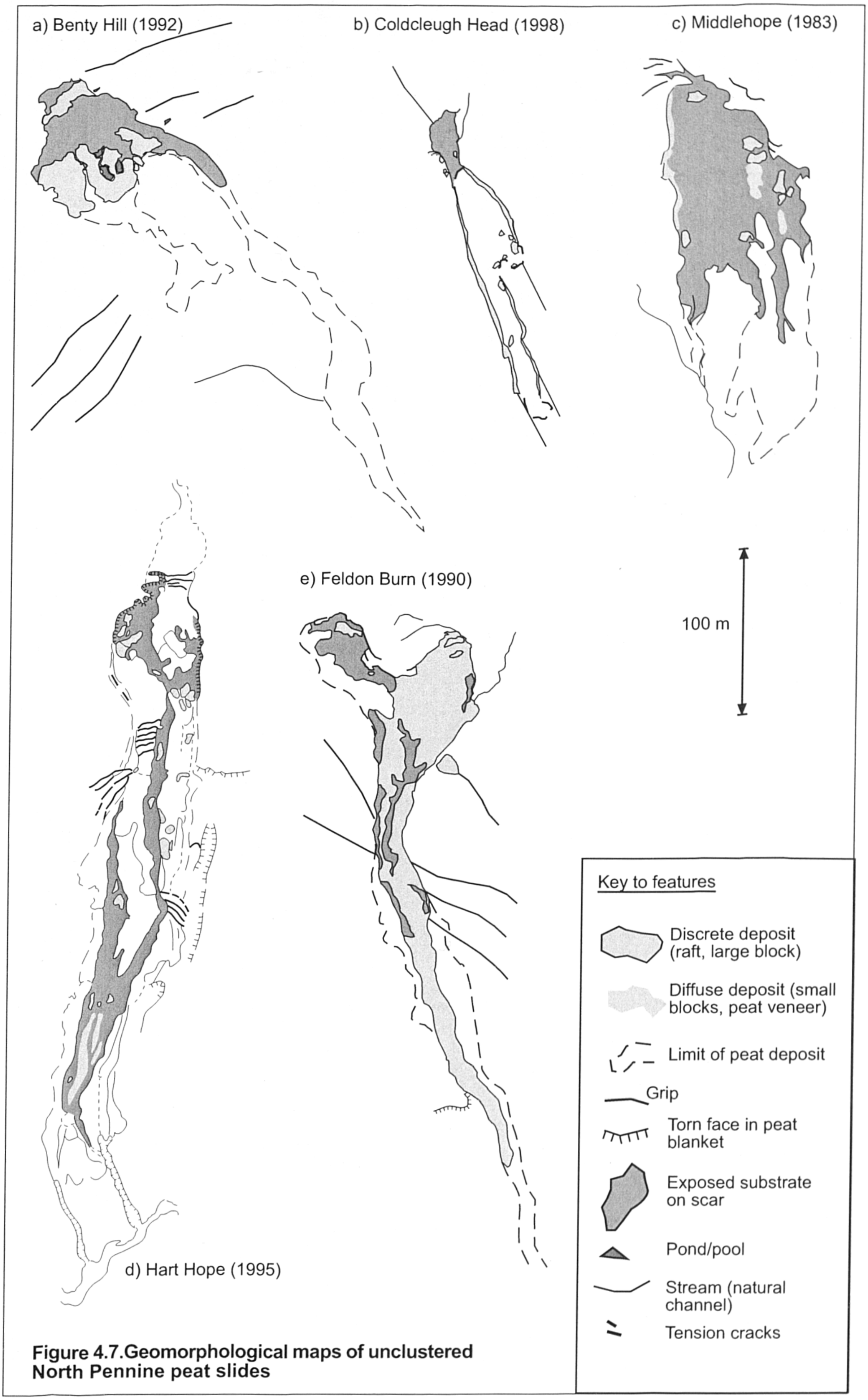


Figure 4.7.Geomorphological maps of unclustered North Pennine peat slides

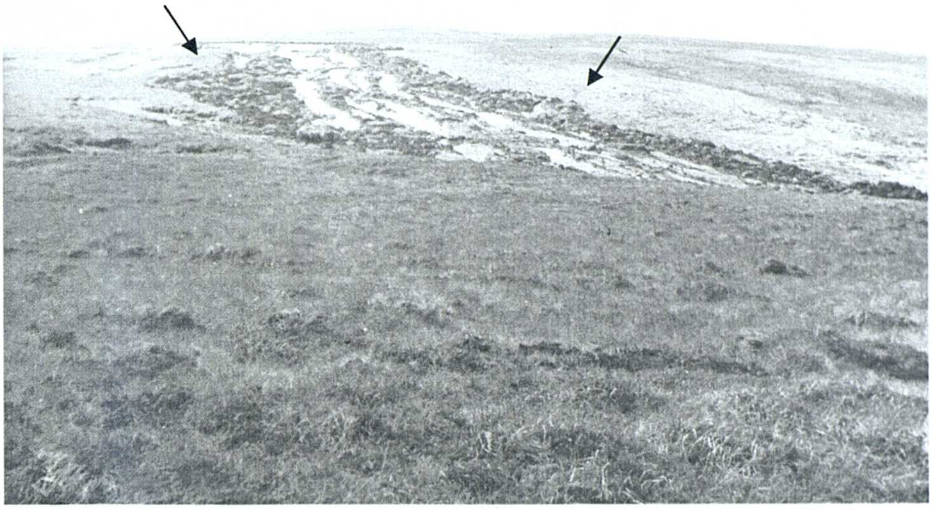
times the length of the scar itself. Large rafts of deposit have become jammed in the lower part of the main scar, and the eastern margin of the scar area is heavily cracked.

Nein Head 2 (Figure 4.6a) consists of two main scar areas, the upper retains a large mass of broken and rafted peat debris on its lower easternmost side. The lower scar exhibits no major rafts, and the deposit area beneath this scar is extensive. Grips that can be traced to either side of the upper failure appear to have been breached by the slide. This is examined further in Chapters 5 and 6. There appears to be major tear set back from the scar margin, but cracking is limited.

The remaining Noon Hill slides comprise Langdon Head (Figure 4.6c) and Langdon Beck (Figure 4.6d). The former occurred during the same thunderstorm as the previous three failures, and is the most extensively rafted of the peat slides studied in the North Pennines. It is characterised by two distinct areas, the upper zone which remains largely occupied by a slightly dislocated deposit, and the lower zone which is largely excavated. The deposit area of the feature is limited by the presence of Langdon Beck stream onto which the scar area joins at its base. Occurring well down from the summit of Noon Hill, Langdon Head is fed by a significant flushline that joins the feature at its upper right bank side. The smaller Langdon Beck failure is the least significant of the North Pennine failures, and is morphologically simplistic. It lacks evidence of deposit (the scar discharging over steep mine spoil), and consists of a simple rectangular scar with a single tear on its left hand side margin.

Figures 4.7a and b show the Meldon Hill peat slides, recorded by Crisp *et al.* (1964). A thunderstorm on the evening of 6th July 1963 was responsible for their occurrence (Crisp *et al.*, 1964). Although field evidence of peat is largely absent at the present day, Crisp *et al.* describe both failures as exhibiting extensive blocky deposits, and the east failure as having significant lateral levees for most of its length. This is supported by photographs taken shortly after the event (Figure 4.9). Both failures feed into the heads of local burns that supply Cow Green reservoir, but there is little significant natural or artificial drainage into either failure.

The Stainmore failures, Iron Band and Dow Crag, represent two of five failures described in the Stainmore area. Hudleston (1930) noted the presence of four 'cloudbursts' running in a chain to the south-east of Iron Band. Again, the 'cloudbursts' occurred during a thunderstorm on June 18th, 1930. Three of the four (originally noted A, B and D) were examined by this author in the field. Access to C was not possible. Of the former three, B and D were insignificant, and appeared to be small slump a



b

Figure 4.9. Meldon Hill East scar (1963), shortly after failure: a) scar area with pronounced lateral deposits clearly visible (arrowed); b) upper track, deposit largely sub-block in size (Photos by permission of J.Adamson, 2001).

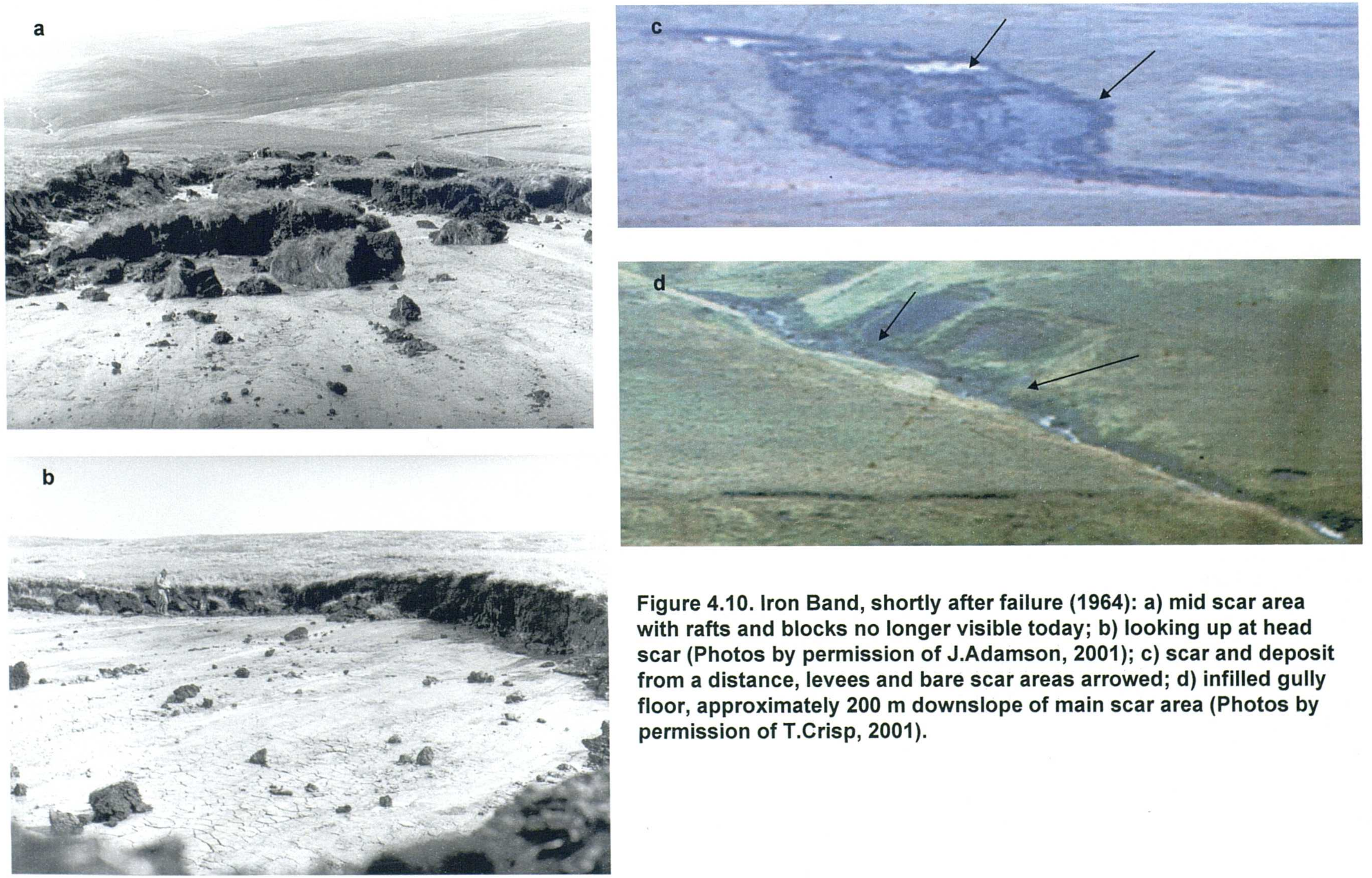


Figure 4.10. Iron Band, shortly after failure (1964): a) mid scar area with rafts and blocks no longer visible today; b) looking up at head scar (Photos by permission of J.Adamson, 2001); c) scar and deposit from a distance, levees and bare scar areas arrowed; d) infilled gully floor, approximately 200 m downslope of main scar area (Photos by permission of T.Crisp, 2001).

features. Slide A (Dow Crag) was one of two larger failures noted by Hudleston, and although very indistinct on the ground was significant enough in morphology to be identifiable as a peat slide. The scar area is characterised by two zones occupied by slightly dislocated rafts, both of which exhibit cracking around their peripheries. The scar areas pinch out downslope, and shallow blocky deposit may be traced spreading out from a bottleneck along the line of a probable infilled gully (marked on the map). The relative clarity of the scar area marked 'secondary?', and the absence of it in the description by Hudleston of an elongated crescent shaped scar, may suggest a period of secondary movement some years after the original failure.

Little information is available concerning the Iron Band failure, other than its probable occurrence in 1964. On the ground, the scar area is an elongate ellipse, and peat deposits can be traced downslope towards a gully feeding Petty Gill. The photographs in Figure 4.10, taken shortly after the event, suggest that the scar area was more infilled than the map portrays. The diffuse peat deposit marked on the map may be highly weathered remains of former rafts.

Finally, Figure 4.8 shows the spatially discrete features distributed across the North Pennines, all of which occurred after 1983. Middlehope (Figure 4.8c) near Allenheads comprises the first of these, and although unpublished, was noted by Johnson (1992), and stated by the landowner as having occurred during the same rainfall event as the 1983 Noon Hill slides. The disturbed area feeds into a small stream, Black Sike. The slide comprises a largely excavated scar area. Small, infrequent blocky deposits are present in the main scar area, while cracking concentrates around the upper right hand side margin. The deposit zone is small in the immediate vicinity of the scar, but blocks have been traced in the adjoining valley for at least two kilometres downstream.

Feldon Burn (Figure 4.8e) occurred in 1990 near Muggleswick, during a thunderstorm on the afternoon of 24th August (Johnson, 1992). The twin scar zones occurred slightly above the head of White Sike, a small stream feeding the larger White Sike. The two scar zones differ significantly in character, the left scar, largely infilled with very blocky deposit, and the right bank scar smaller but excavated to a greater extent. Downslope of their confluence, the scar area is extensively covered by channelised peat deposits which distributed parallel to the axis of White Burn for much of its length. Three sets of grips draining the hillside have been disrupted by the failure. Cracking is more extensive around the less excavated scar area.

Benty Hill (Figure 4.8a), up-valley from Alston, was documented by engineers clearing the road of a peat deposit in January 1992 (pers. comm. J.Gray, 1998). The scar area exhibits at least four major rafted sections, none of which has moved any great distance. The blocky deposits are concentrated in two distinct lobes, one running downslope of the rafted section, and the second following the line of Mere Sike to the A 686. Gripping is visible in the vicinity of the scar area but cannot definitely be traced into it.

The Coldcleugh Head failure (Figure 4.8b) has the smallest scar area of all fourteen slides. However, it has an extensive deposit characterised by clear levees that bound much of the smaller block zone. Cracking is minimal. One major grip runs through the main scar area. Again unpublished, reports from land managers suggest that the failure occurred in the last quarter of 1997 or the first quarter of 1998.

Finally, the Hart Hope failure (Figure 4.8d) is a particularly complex feature exhibiting at least three slope segments, all of which are partially infilled with rafted peat deposits. The Hart Hope failure was first reported by Warburton and Higgitt (1998) and occurred in February 1995 in conjunction with rainfall and snowmelt. Cracking occurs in parallel bands at several locations from head to toe of the feature. Although the landslide is fed by a large flushline, there is little evidence of other, artificial drainage into the site.

Although extensive field-mapping has been undertaken at each site, it is not proposed to examine case-by-case the nature of each peat slide. Instead, comparable summaries of the main peat slide characteristics provide a means of assessing the general nature of the population as a whole. This brief comparison of North Pennine slides has illustrated that the range of features first defined in Chapter 2 varies widely within the limits of their definition. In an attempt to refine what is known about slides, subsequent sections examine the morphological and morphometric characteristics of these slide components. For ease, discussion revolves around features comprising the scar area in the first instance, and then features dominating the deposit area. Rafts are an intermediary form.

4.2.3 Scar and deposit morphometry

Chapter 3 highlighted the use of Crozier's landslide morphometric indices for excavation, extension and dilatency (or lateral spreading). Summary figures for Crozier's indices are shown in Table 4.6. An explanation of the derivation of the indices is provided in Chapter 3. These indices may be supplemented with other measures of morphometry (length/width ratio and excavation ratio) to define the dimensions of the scar area. Crozier's indices will be examined first.

Most of the values show good correspondence with the mean index values for Crozier's planar slide. This is the form which corresponds most closely to that described for peat slides in the previous chapter. The depth index is the first described. The shallowest failures are Nein Head 2 (0.18) and Benty Hill (0.15). The left bank scar at Feldon Burn is shallow, but the intermittent and lengthy scar is not excavated to the same extent as the other slides, and the index is a mis-representation of the morphometry of the failure. Excluding the Feldon Burn right bank scar for the same reasons, the remaining failures fall closely around the mean (s.d.: 0.32).

The dilation index indicates that most failures exhibit slight lateral spreading with deposition (m: 1.24). Examination of the geomorphological maps in Figures 4.6 to 4.8 however, suggests that many of the slides are channelised in their deposit zones, and that the occurrence of lateral deposits around the wide scar areas leads to an over-representation of maximum deposit width, and an over-estimate of spreading.

Flowage is not considered for planar slides by Crozier, and hence the values shown on Table 4.6 cannot be compared. However, as a composite index of dilation and tenuity, flowage would be expected to magnify the errors inherent in both.

Displacement corresponds adequately to the scar excavations shown on the maps. The greatest values are shown for the sites with greatest excavation (Meldon Hill East, Dow Crag and Langdon Beck). Sites with intermediate levels of deposit removal, such as Nein Head 3, Benty Hill and Middlehope, show lower values (between 0.26 and 0.29). Problems arise where there is significant deposition in the upper reaches of slide scars, such as at Langdon Head and Meldon Hill West. The index suggests practically no excavation due to the presence of slightly mobilised deposit in the upper scars. However, both sites are extensively excavated in their lower reaches.

Downslope extension, represented by the tenuity index (m: 1.5) suggests that the North Pennine slides fall somewhere between planar slides (m: 1.17) and viscous flows (m: 1.71). On the basis that peat slides are more fluid than debris slides but initiate as planar slides, this may be a reasonable representation of process. Benty Hill, Coldcleugh Head and Nein Head 3 display the greatest downslope extension relative to their scar lengths, while Feldon Burn and Langdon Beck display the least. Again, the

Table 4.6. Morphometric indices for peat slide sites, after Crozier (1986).

	Crozier's Indices					Scar area characteristics		Other Indices		
Slide name	Depth	Dilation	Flowage	Displacement	Tenuity	Scar area (m^2)	Concealed by deposit (m^2)	Scar excavation index	Width/length ratio (scar)	Width/length ratio (dep)
Benty Hill	0.15	1.00	274.67	0.29	2.75	4400	1660	0.38	0.55	0.20
Coldcleugh Head	0.22	2.00	361.70	0.53	3.62	679	10	0.01	0.36	0.20
Dow Crag	0.23	1.40	154.55	0.73	1.55	8298	1677	0.20	0.27	0.25
Feldon Burn (LB)	0.18	1.23	57.69	0.00	0.58	9561*	6582*	0.69	0.15	0.15
Feldon Burn (RB)	1.53	1.20	92.50	0.08	0.93	-	-	-	0.50	0.65
Hart Hope	0.21	1.23	101.49	0.10	1.01	10442	1535	0.15	0.15	0.18
Iron Band	0.26	0.94	137.17	0.18	1.37	3153	45	0.01	0.32	0.22
Langdon Beck	0.26	1.23	57.69	0.58	0.58	2501	94	0.04	0.27	0.57
Langdon Head	0.30	1.00	100.00	0.00	1.00	34137	20179	0.59	0.28	0.28
Meldon Hill East	0.24	1.23	82.76	0.41	0.83	5173	1089	0.21	0.12	0.18
Meldon Hill West	0.21	1.77	100.00	0.05	1.00	9553	1483	0.16	0.11	0.20
Middlehope	0.25	0.88	116.13	0.26	1.16	10390	1849	0.18	0.52	0.39
Nein Head II	0.18	1.40	147.89	0.11	1.48	20468	3029	0.15	0.21	0.20
Nein Head III	0.24	1.22	298.70	0.26	2.99	4934	2144	0.43	0.35	0.14
West Grain (LB)	0.49	1.20	184.62	0.20	1.85	7082*	4857*	0.69	0.31	0.20
West Grain (RB)	0.38	1.04	134.43	0.07	1.34	-	-	-	0.22	0.17
North Pennine mean values	**0.33**	**1.24**	**150.12**	**0.24**	**1.5**	-	-	**0.28**	**0.29**	**0.26**
Crozier's (1973) mean values for planar slides	7.66	0.95	-	79.87	1.17	-	-	-	-	-

* values for scar area as a whole

index is probably a mis-representation of the situation at Feldon Burn, while there is some doubt as to the true deposit length at Langdon Beck given the reworking of the hillside by mining immediately beneath the failure. As a consideration of the entire slide set, the index performs satisfactorily.

Although scar excavation may be expressed purely as a proportion of downslope length (such as in Crozier's indices), it is more precisely described as a proportion of the scar area still covered by peat, whether transported or in situ. Table 4.6 summarises scar area in m^2 for each slide, the areas covered in deposited and in-situ peat, and a value for scar excavation that represents a summary of the three figures. Excavation is greatest at Iron Band, Langdon Beck and Coldcleugh Head, and least at Feldon Burn, Langdon Head and West Grain. The high excavation at Iron Band may in part reflect the lack of present surface evidence of slide deposit. Figure 4.9a suggests that the slide scar was formerly occupied by significant bodies of peat. At the sites exhibiting low excavation, Langdon Head and West Grain are heavily rafted, while Feldon Burn is largely comprised of blocky deposit; the excavation ratios are similar, the character of the scar areas is different. If the excavation ratio is correlated with the value for displacement from Crozier's scheme, the correlation is poor (r^2: 0.20). This suggests that if excavation is highly variable both in nature and between sites, it should be expressed as an area ratio, as this is a value more directly derived from actual slide dimensions.

Width length ratios of the scar areas suggest that they are always elongate (m: 0.29), with some slides being highly extended (Feldon Burn, Hart Hope and the Meldon failures). The extent to which this may be a product of hillslope position is considered in the next section. Width/length ratios of deposit (that has not entered fluvial networks) suggests that deposits are more elongate than their associated scar areas (m: 0.26).

4.2.4 Characterisation of morphological units

The morphology of slide scars is reflected partly in their dimensions, as discussed previously, but also in the characteristics of the scar margin and its immediate locality. Cracks, tears and ridges are found at some of the sites, and a brief discussion of these follows.

4.2.4.1 Tension features

While the presence of scar areas is the most significant manifestation of tension, around them are found other tension features such as cracks and tears. Cracks are relatively narrow and deep features, whilst tears are wider surface features that can be likened in appearance to tears in fabric. Photographs of both can be found in Chapter 2 (Figures 2.7 and 2.10).

Crack and tear dimensions for Nein Head 2 and Nein Head 3 are shown in Table 4.7. Only two examples are used, because of the uncertainty over origin of the tension features at many of the sites. The quality of air photographic coverage taken soon after the two Noon Hill failures permitted calibration of the ground features. Both displayed a similar number of cracks and tears in the periphery and adjoining their scar areas. Lengths range from 1.5 to 10 m at Nein Head 3 and 0.2 to 7.5 m at Nein Head 2. Depths range from surficial features (minimum 0.15 m) to cracks extending to the full local depth of peat (1.5 m in an adjoining crack at Nein Head 2). Widths again vary from hairline cracks 0.05 m at the surface to wide tears in excess of 1.0 m.

Slide name	Number of tension features	Mean width (m)	Mean depth (m)	Mean length (m)
Nein Head 2	15	0.45	0.49	1.86
Nein Head 3	19	0.88	0.46	4.75

Table 4.7. Crack and tear dimensions for Nein Head 2 and Nein Head 3

Some cracks are surficial (a few centimetres deep), but lengthy and sinuous. Other cracks are deep and narrow, often narrower at the top than below. Water-filled cracks are frequently found in the peripheries of scar margins (particularly at Benty Hill), and also within the fractured parts of larger rafts. Large pools may develop in crack-like features that are products of jammed together rafts rather than tensional splitting of the peat surface.

Crack position is also variable, with many cracks joining the scar edge, usually obliquely, and others set back and parallel. Both connected and disconnected cracks occur at a variety of orientations with respect to the local scar margins. The geomorphological maps in Figures 4.6 to 4.8 indicate that cracks at some sites are clustered to one side of the scar area (e.g. Nein Head 3, West Grain, Meldon Hill East and West, and Middlehope). In most of these cases, the cracks themselves are clustered in small areas, suggesting that while there are preferential zones of compression (manifest as ridges and concentrations of deposit), there are also preferential zones of tension.

In some cases, cracks are found which suggest the initial stages of segregation of the peat mass into block forms. Crack patterning of this nature has been photographed at Feldon Burn and just above the head zone of the Slievenakilla failure in Northern Ireland (Figure 2.7).

Tears are shallower and wider than cracks. The ragged edges found around Nein Head 2 and 3, echoed at other sites, can also be found on Wilson and Hegarty's (1993) slide maps, and it is these that are usually described as tears in the field. In bog bursts, wide and deep tears define the disturbance areas, and they are probably one of the most diagnostic features of bog bursts.

4.2.4.2 Compression features

Where debris impacts with the scar margin, and where compressive forces dominate in the periphery of the scar, compression features may develop. These are usually either upthrust margins (Figure 4.11a) or compression ridges (Figure 4.11b). Because they are not common, it is difficult to summarise their attributes in anything other than qualitative terms.

Upthrust margins occur where dislocated masses of peat drive upwards scar marginal peat which is loosely connected to the underlying substrate. This results in an upfolded peat mass supported by another (usually large) rafted peat deposit. These have been observed at Nein Head 3 and on the left bank margin of the right bank scar of West Grain.

Compression ridges comprise single or multiple ridges in peat that is otherwise undisturbed. The peat has disconnected from the substrate and rippled under the build up of compressive forces within the scar margin. Occurrence is almost exclusively within thinner peat areas, where the bog may fold like skin. Rippled compression ridges have been recorded at Hart Hope and a single ridge at West Grain. In both cases, the surrounding peat is under half a metre thick. It seems unlikely that

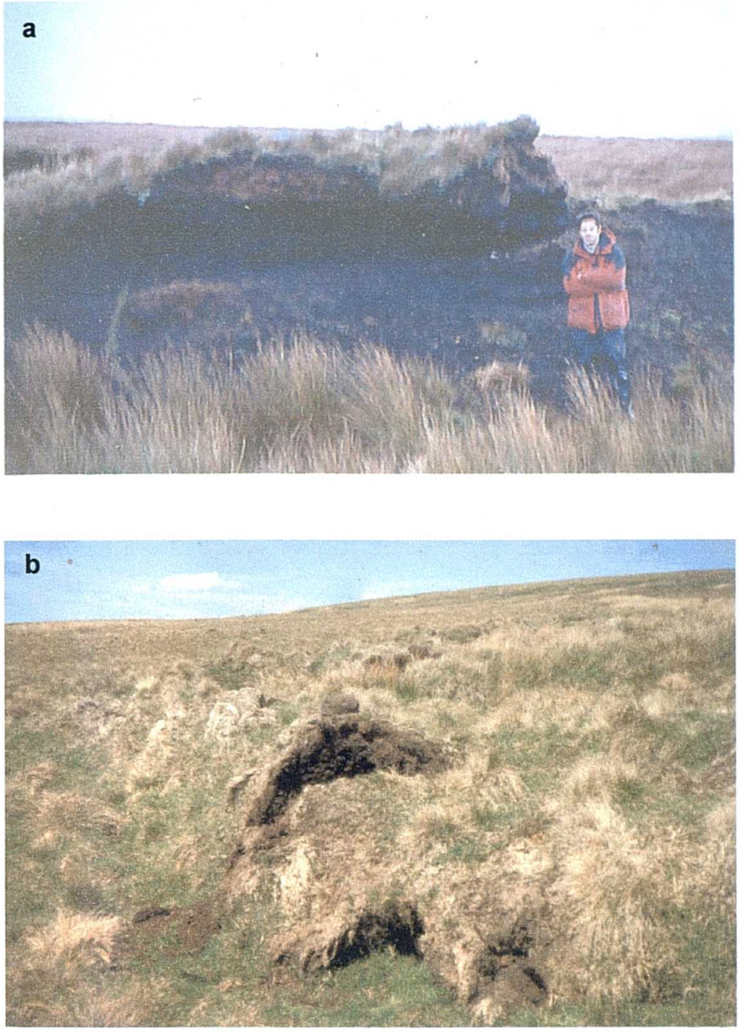


Figure 4.11. Compression features at slide scars: a) upthrust margin, b) compression ridge.

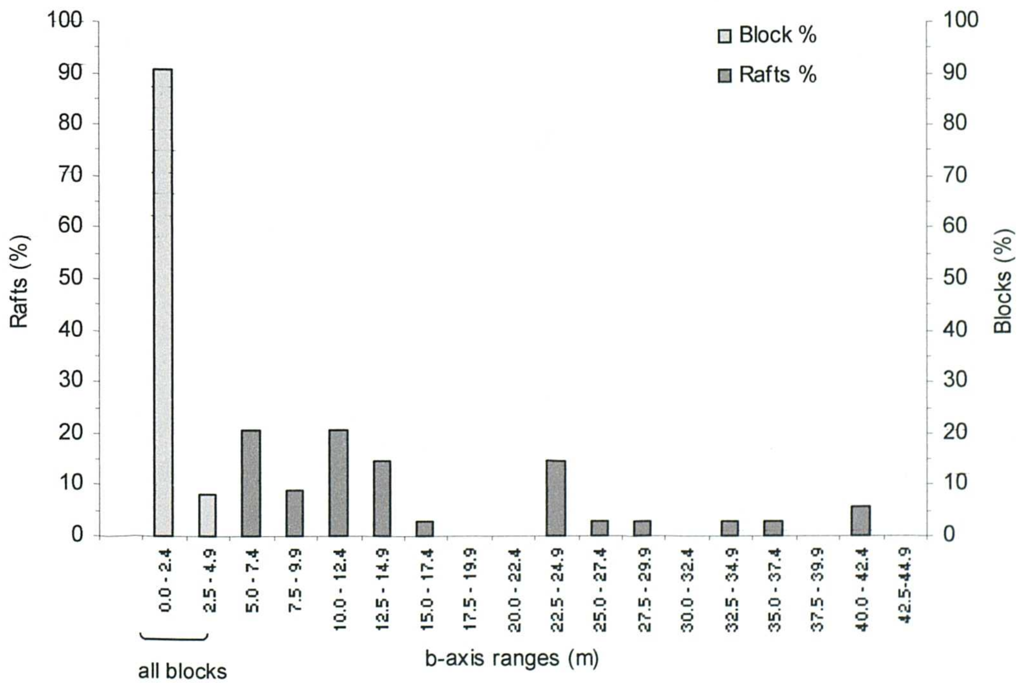


Figure 4.12. Block and raft b-axes percentages for all sites.

compression ridges are able to form in deeper peat, and this may explain the lack of their occurrence at other sites.

4.2.5 Peat slide non-slurried deposits

Material which has been transported will at some point be redeposited. Deposit types in the past have been divided for simplicity into rafts, blocks and slurry. This section considers the form characteristics of rafts, blocks and slurry, and the justification for their separate consideration. Deposit is considered from the most coherent solid deposits (rafts, blocks) to the least coherent slurried debris. Runout characteristics of block deposits are dealt with extensively in Chapter 5, while raft movement is covered initially in this section because of the close correspondence between raft shape and scar form.

4.2.5.1 Rafts

Rafts are frequently described in peat slide and bog burst research, though no attempt is made to provide a definition by which they may be identified either in the field or on aerial photographs. Most usually, rafts are regarded as the largest displaced peat deposits, but their implied form is similar to blocks, as is their likely mode of movement (sliding). The geomorphological maps presented earlier in Figures 4.6 to 4.8 suggest that peat slides in the North Pennines fall into two main categories - those exhibiting extensive large intact peat masses (raft dominated), and those which are almost entirely excavated, and in which deposit size is small and relatively uniform (block dominated).

The extent to which the disturbed peat blanket exists during failure as rafts and/or blocks may be highly significant in terms of the sediment budget of the event, and in implication for process. For example, the lack of rafts found outside slide scar areas suggests that the relatively intact raft deposits are not able to withstand large transport distances (and by implication, high velocities). Hence, the presence of rafts may be indicative of process vigour during the failure. There are a number of questions pertinent to an understanding of the role of rafts in peat slides:

i) What pre-failure characteristics of the peat blanket govern raft morphology?

ii) At what point do rafts become blocks?

iii) Do rafts exhibit features which indicate modes of block formation?

iv) What are the processes which arrest raft movement?

For rafts and blocks to be discussed separately, some criteria is required for their definition. Field sampling of discrete solid peat masses suggested that a majority of the turf-topped deposit elements were relatively small (b-axis < 5 m). Larger pieces of debris (b-axis > 5 m) were often only partially disconnected from the blanket margin, or still connected to other pieces of transported material. This chapter assumes an arbitrary b-axis cut-off of 5 m, and attempts to qualify this initial field-based classification through analysis of deposit characteristics.

On the basis of the wider literature support for rafts as the 'largest' deposits, Figure 4.12 presents block and raft b-axes measured from all North Pennine sites. The sample size of surveyed blocks is considerably larger than that for rafts (over 1000 blocks compared with under 40 rafts). Distributions of both can be compared if the number of blocks and rafts falling into specified size ranges are expressed as percentages of the total counts rather than as absolute frequencies. Figure 4.12 illustrates all sampled 'blocks' and 'rafts' at b-axis size ranges of 2.5 m. Over 90% of all blocks fall into the 0 - 2.49 m b-axis range, with nearly all the remainder (8%) in the 2.5 - 4.9 m range. Rafts, as identified in the field, fall mainly between 5 and 15 m in b-axis, with none at all below 5 m in b-axis.

For the remainder of this chapter, rafts are considered as deposits with a b-axis in excess of 5 m. The physical basis for the division of rafts and blocks reflects limits imposed by raft dimensions, in that they can neither roll nor tilt to any significant degree. Blocks are defined as deposits with a b-axis less than 5 m, and which have the ability to tilt or roll. The form basis for this distinction is reconsidered at the end of the chapter.

Initial control of raft form is likely to be a function of origin within the failed peat mass. Reconstruction of raft source positions is possible where rafts have not been extensively broken in movement, and where transport distance is small. In these cases, raft edges may be visually fitted to scar edges. Figures 4.13a to e show peat slide scar areas post-failure (on the right hand side), with raft positions reconstructed into hypothesised positions prior to failure (on the left hand side). Raft forms have been traced from aerial photographs for all slides in which significant rafting is clearly visible. Scar areas have also been traced and inferred for the locations in which rafts can be seen to impinge on the scar margin. Both the extent to which rafts comprise the scar areas, and the manner in which they moved can be determined from these reconstructed maps. Table 4.8 shows raft specific details, including dimensions, maximum travel distance given likely origin, and classification of form based on disturbance, described shortly. These details may be compared with the reconstructed forms on Figure 4.13.

Preserved raft forms are visible at Benty Hill, Langdon Head, Nein Head 2 and 3, and West Grain. At these sites, many of the forms can be clearly related to local scar margins. For example, at Nein Head 2 (Figure 4.13d) a major peat mass comprised of rafts 2 to 7 has fragmented and come to rest over the lower right bank margin. The peat mass as a whole is 65 m long and 57 m wide. Correspondence between the upper scar edge and the upper edge of the raft is good. Raft 1 has been displaced very little, and probably originates from the upper left corner of the scar area. Equally, at Benty Hill and Langdon Head (Figures 4.13a and e), potential raft origins are limited by either scar size (Benty Hill) or travel distance (Langdon Head), and original positions can be reconstructed with reasonable confidence. Where rafts have travelled greater distances (e.g. rafts 4 - 7, Nein Head 3), assessment of origins is more difficult. The degree of fracture appears to be greater, and the raft margins more disturbed by tearing and abrasion.

Peat blanket features prior to failure may also influence raft form, for example, where grips cut through the former intact peat body. At Benty Hill, a grip reconstructed along its former axis would have acted as a line of weakness, and as the lower edge of rafts 2 and 3. However, grips at Nein Head 2 do not appear to have influenced raft form (also visible on Figure 4.5).

When rafts are preserved, they can make up a considerable volume of the mobilised peat body. For example, the extent of rafting at Benty Hill as a proportion of the total scar area suggests that only a small area of the displaced mass was transported a significant distance. Maximum raft sizes range between 93 x 40 m (raft 8, Langdon Head) and 35 x 14 m (raft 1, Nein Head 3). Raft depths (based upon edge measurements in the field) are between 0.5 - 1.0 m (at West Grain) and 1.2 - 1.5 m (at Nein Head 3). Maximum rafts sizes reported at other peat failures (see Chapter 3) range between 57 and 7 m (m: 23 m) a-axis and 42 and 2.5 m (mean: 15.66 m) b-axis. These are consistent with the raft sizes reported previously.

Table 4.8. Raft form characteristics and mode of deposition

Raft number	a-axis (m)	b-axis (m)	Maximum travel distance (m)	Slide name	Raft type*	Means of arrest*
1	18.5	6.5	1.00	Langdon Head	Intact	Separation
2	21.8	7.3	1.00	Langdon Head	Intact	Separation
3	19.4	11.3	1.00	Langdon Head	Intact	Jamming
4	17.7	12.9	6.45	Langdon Head	Pre-block	Momentum
5	11.3	9.7	20.97	Langdon Head	Intact	Momentum
6	6.5	6.5	16.13	Langdon Head	Intact	Momentum
7	12.9	5.6	1.00	Langdon Head	Fractured	Momentum
8	93.5	40.3	1.00	Langdon Head	Intact	Separation
9	29.0	12.9	1.00	Langdon Head	Pre-block	Jamming
10	80.6	40.3	1.00	Langdon Head	Intact	Separation
11	32.3	24.2	56.45	Langdon Head	Pre-block	Momentum
12	19.4	12.9	45.16	Langdon Head	Intact	Momentum
13	16.1	11.3	45.16	Langdon Head	Fractured	Momentum
14	16.1	11.3	64.52	Langdon Head	Intact	Momentum
1	24.6	10.8	10.77	Nein Head 2	Intact	Momentum
2	55.4	24.6	46.15	Nein Head 2	Intact	Jamming
3	41.5	23.1	46.15	Nein Head 2	Intact	Jamming
4	35.4	35.4	46.15	Nein Head 2	Pre-block	Mounting
5	35.4	23.1	46.15	Nein Head 2	Fractured	Mounting
6	47.7	27.7	96.92	Nein Head 2	Pre-block	Mounting
7	36.9	10.8	50.77	Nein Head 2	Pre-block	Momentum
1	85.5	34.8	5.07	West Grain	Intact	Separation
2	27.5	15.9	17.39	West Grain	Pre-block	Momentum
3	46.4	23.2	17.39	West Grain	Intact	Jamming
4	14.5	8.7	17.39	West Grain	Intact	Momentum
5	20.3	5.1	18.84	West Grain	Pre-block	Momentum
6	33.3	11.6	3.62	West Grain	Intact	Momentum
1	35.7	14.3	60.0	Nein Head 3	Fractured	Jamming
2	24.3	12.1	60.0	Nein Head 3	Pre-block	Jamming
3	27.1	27.1	64.0	Nein Head 3	Pre-block	Mounting
4	16.4	5.7	90.0	Nein Head 3	Intact	Mounting
5	14.3	6.4	120.0	Nein Head 3	Intact	Mounting
6	11.4	7.9	100.0	Nein Head 3	Intact	Jamming
7	21.4	14.3	112.0	Nein Head 3	Fractured	Jamming
1	40.0	10.0	8.0	Benty Hill	Intact	Separation
2	44.0	34.0	40.0	Benty Hill	Intact	Mounting
3	48.0	34.0	36.0	Benty Hill	Fractured	Mounting
4	30.0	18.0	42.0	Benty Hill	Intact	Jamming
5	23.0	8.0	42.0	Benty Hill	Intact	Mounting

* see text, section 4.5.2.3

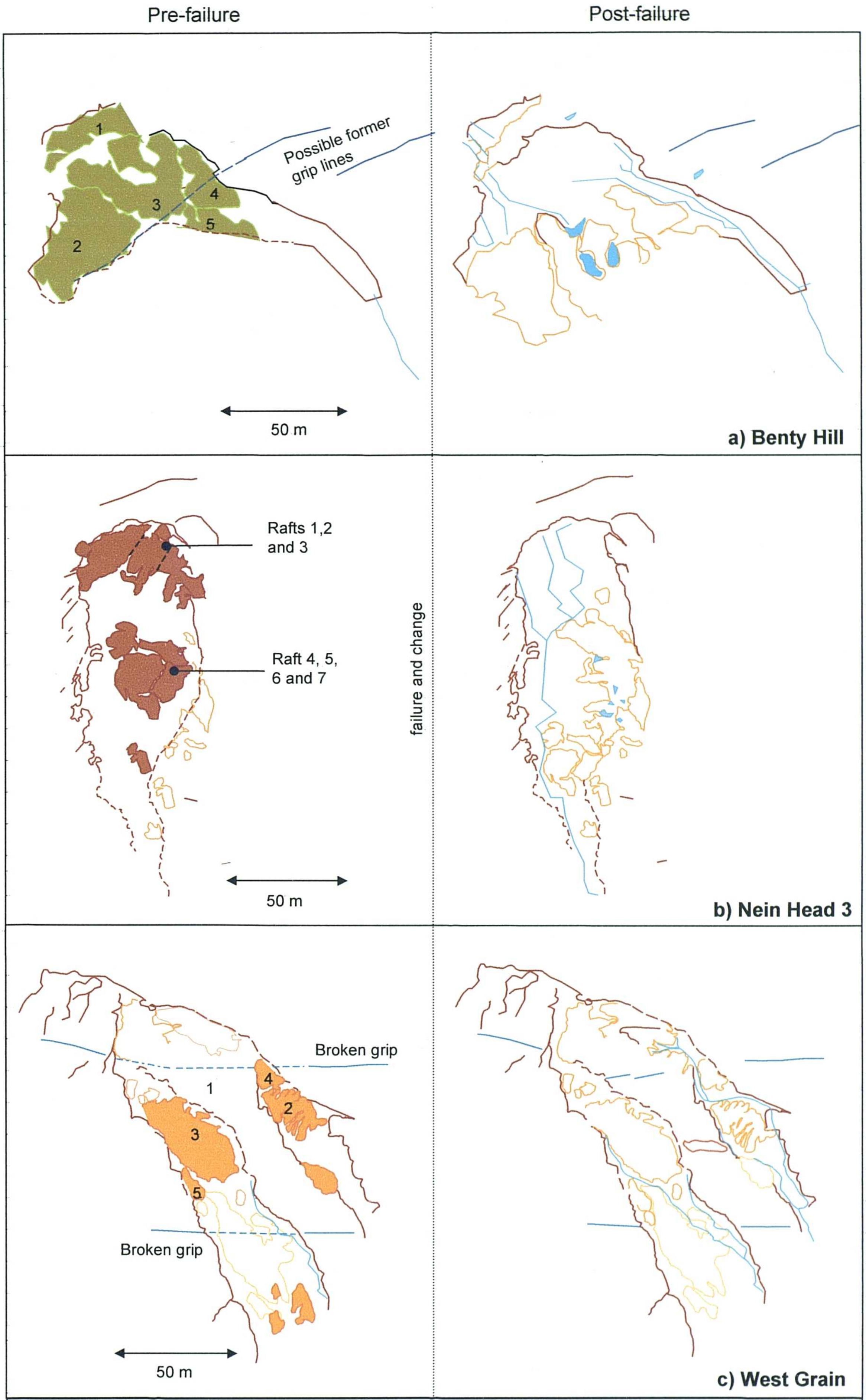


Figure 4.13. Reconstruction of raft positions: left hand column shows estimated raft position pre-failure, and right hand column shows raft positions observed in the field, post-failure.

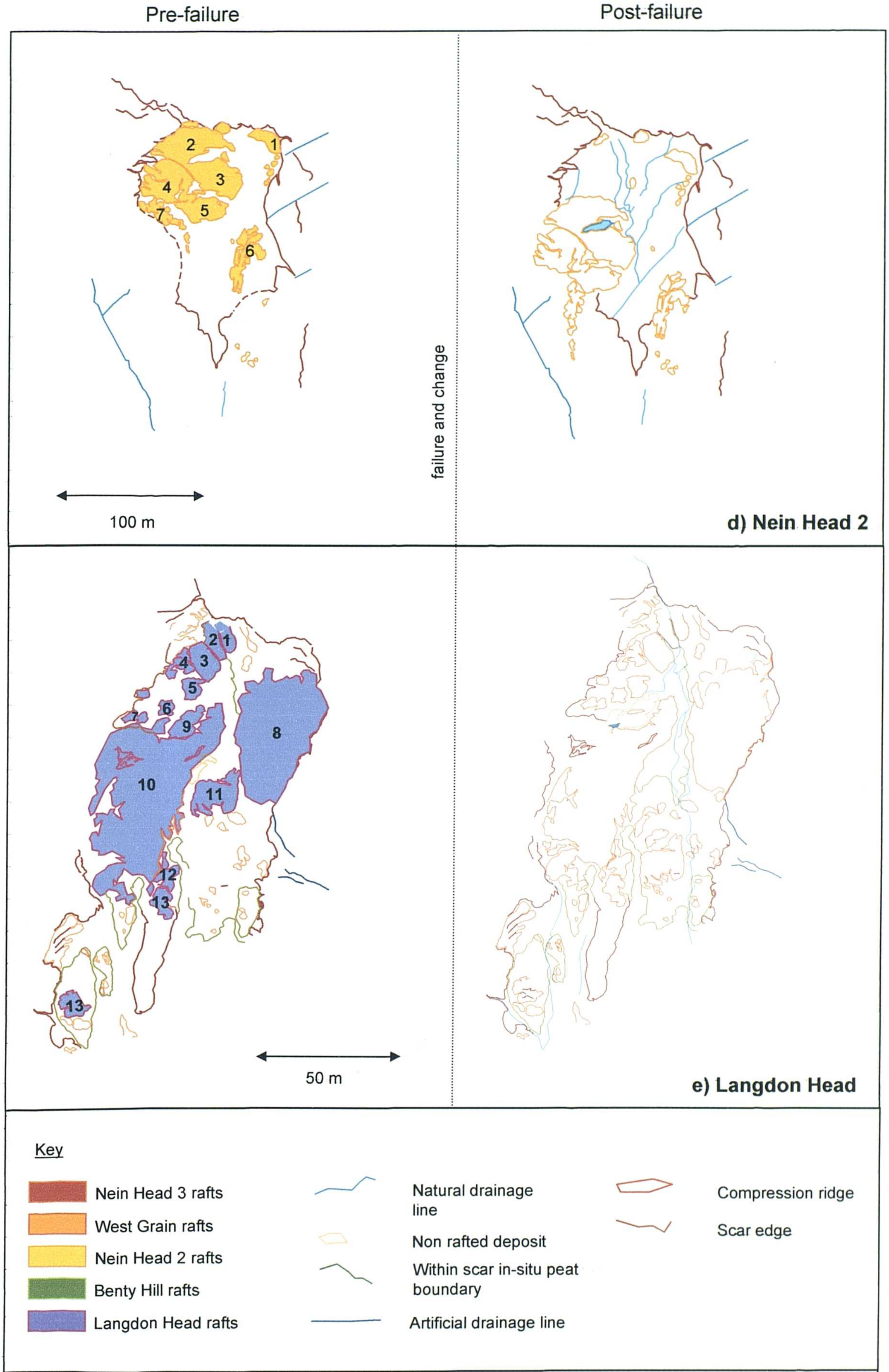


Figure 4.13. continued...

Raft disruption may relate to transport and deposition processes. Figure 4.14 shows all recorded rafts sizes against maximum travel distance, separated by raft structure. Raft sizes are plotted as areas in m^2. A simple, threefold classification system for raft structure is employed, based upon the visual complexity of each raft:

i) **Intact:** these rafts are structurally coherent peat masses, simple in shape and relatively undisturbed other than in having been transported (e.g. Figure 4.13e: rafts 3 and 8).

ii) **Fractured:** such deposits exhibit initial signs of break-up, such as single large fractures that divide the raft into two distinct but joined sections (e.g. Figure 4.13a: raft 3).

iii) **Fragmented:** these rafts are highly fragmented, with sub-components approximating blocks, rather than rafts, in size (e.g. Figure 4.13c: raft 2).

When travel distances and dimensions are plotted by structure, fragmented and fractured rafts comprise much of the middle distance, intermediate sized rafts. The smallest rafts that have travelled the furthest comprise mainly intact and a few fractured rafts, whilst the largest, virtually static rafts are classified intact. Although there is a perceptible decline in raft size with increasing travel distance, there is no statistically significant correlation between the two. It is probable that in the case of the largest deposits, the lack of movement results in little structural disruption. In the case of the smallest deposits, the rafts may be the sub-products of the intermediate/highly disrupted rafts. This evidence suggests that rafted deposits show a trend towards break up with increasing travel distance, and that the transport process influences raft size.

In some cases, the sizes of the sub-components of fractured and fragmented rafts approximate the dimensions of blocks. Sub-components may be defined where a distinct 'limb' of a raft has its discrete area adjoined to the remainder of the raft by under 25% of its bounding perimeter. This means that sub-components are only defined when raft elements are near break-up. Figures 4.15a and b show histograms of raft sub-component and block b-axes. A majority of sub-components fall under 5 m in b-axis (62%), but with a greater percentage of these between 2.5 m and 5 m (37%). The remaining forms are scattered between smaller rafts nearer 5 m in b-axis and larger rafts up to 35 m in b-axis. Comparison with block b-axes (Figure 4.15b)

Figure 4.14. Raft dimensions and maximum travel distance, by raft structure

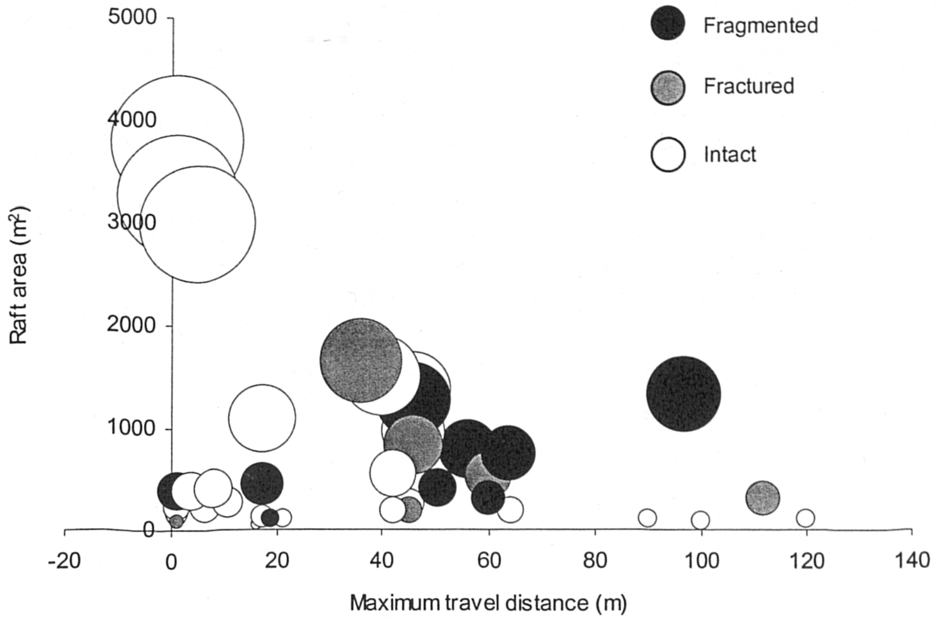
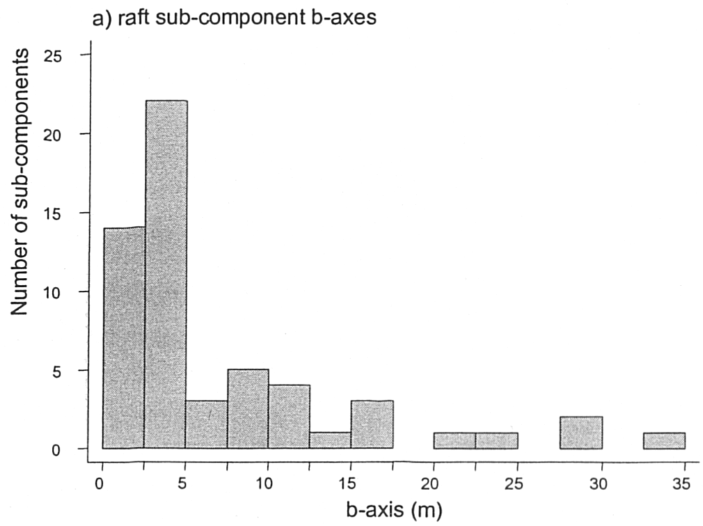
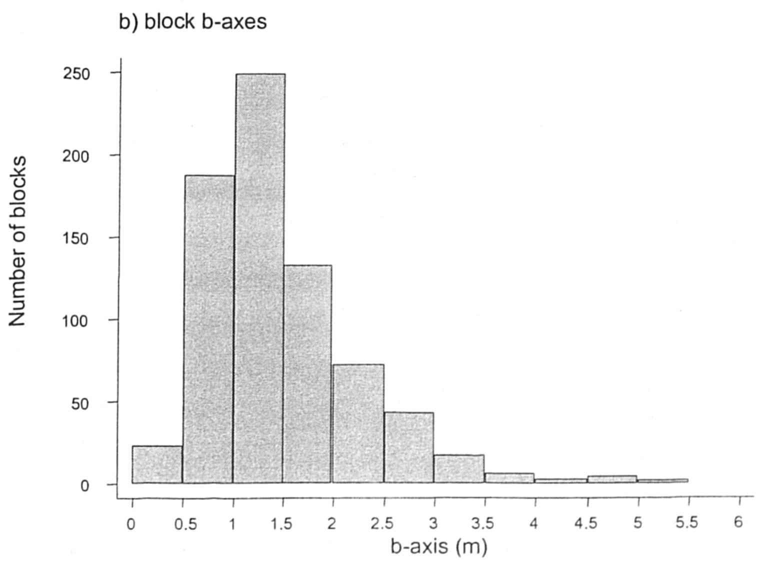


Figure 4.15. Summary histograms of raft sub-component and block b-axes





suggests that the largest sub-component population falls in the intermediate range (2.5 - 5.0 m b-axis) between the peak in block dimensions and the spread of raft dimensions.

It should be noted that the raft dimensions represent those at cessation of transport. There is no way of determining whether the initial displaced peat mass consisted of larger rafted sections of which these are constituent parts, or whether these represent the largest discrete masses of peat involved in the transport process.

The mode of arrest comprises the final control on raft form. For example, at Nein Head 2 (Figure 4.13d), it is probable that the largest joint separating rafts 2 and 3 from 4 and 5 is a result of the forcing upwards of the raft mass as it came to a standstill over the scar margin. At West Grain (Figure 4.13c), a gulf in the peat at the top of the feature is matched by a buckled compression ridge at its lowest extent. Raft positions relative to the scar margins suggest four possible means by which movement ceases:

i) loss of **momentum** without impact: rafts freed to move by the peat around them slide freely within (and beyond) the scar area until frictional forces exceed those driving the rafts downslope (e.g. Langdon Head: rafts 11 and 14).

ii) **mounting** of the scar margin: rafts encounter the scar margin during transport, and in mounting the discontinuity in the blanket, they again lose momentum and stop (e.g. Nein Head 2: rafts 2 - 6; Benty Hill: rafts 2 - 4).

iii) **jamming** on other deposit: friction between slower moving or static rafts and the raft in question cause the latter to jam on the former, coming to rest in the process (e.g. Nein Head 3: rafts 1-5, 7; Langdon Head: rafts: 1-3, 12, 13).

iv) failure to **separate** from scar margin: in several cases, a large rafted mass of peat detaches from the intact blanket, but having rotated slightly, or subsided is unable to move further because it remains partly attached to the blanket (e.g. Langdon Head: rafts: 8 ,10; Benty Hill: raft 1).

Table 4.8 indicates that most rafts arrest through loss of momentum. However, with such a small population of rafts to examine, it is difficult to comment further on the relationship between raft form, travel distance and stress history (as embodied in mode of arrest).

4.2.5.2 Blocks

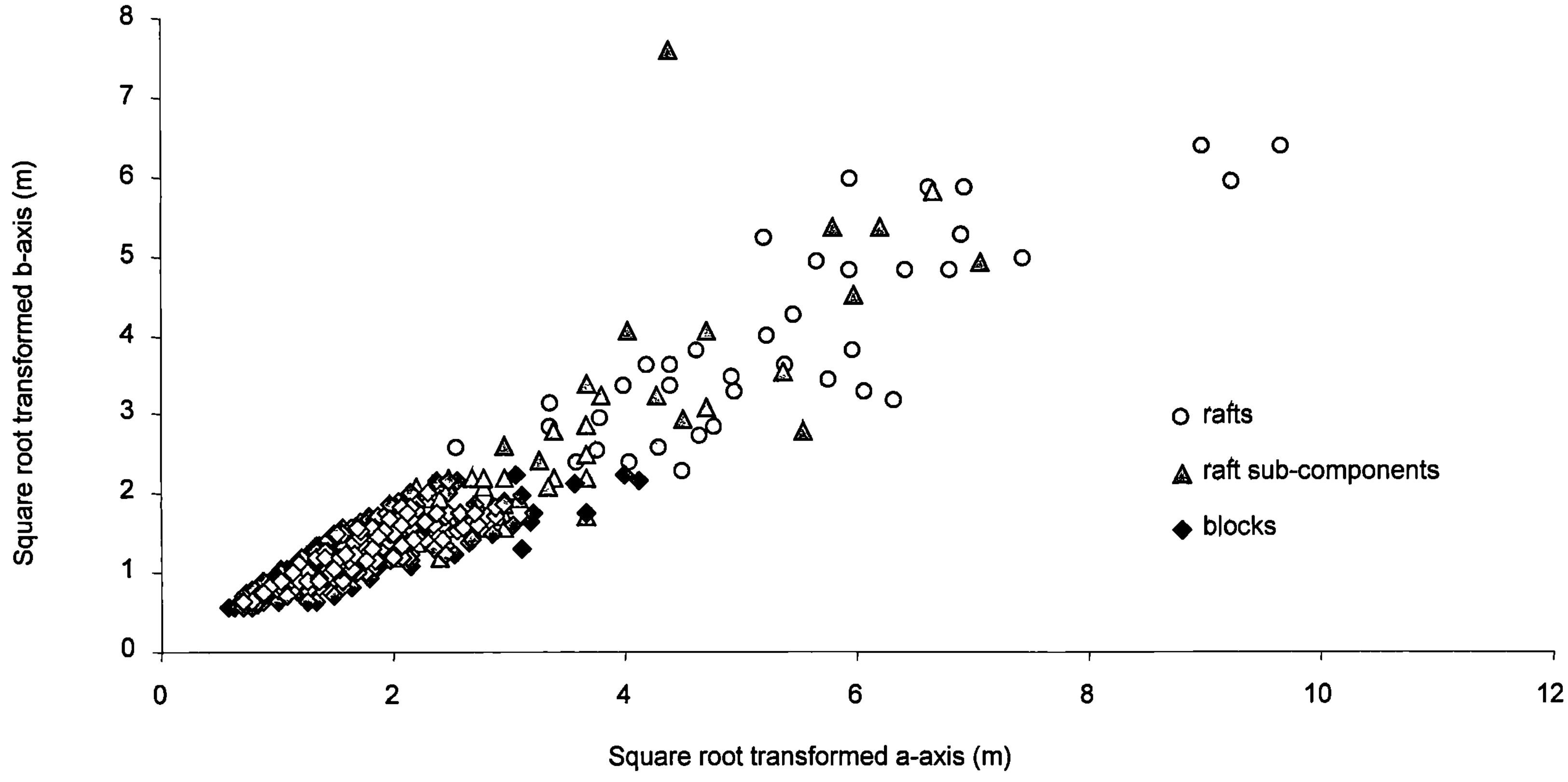
After initial fragmentation of the bog surface into rafts, the transportation and break-up of the remaining disturbed peat continues as blocks. A summary histogram of block b-axes is shown in Figure 4.15b, with the continuum of rafts, sub-components and blocks represented in Figure 4.16. A majority of blocks (> 50%) fall into the 0.5 – 1.5 m range for b-axis, while there are few blocks in excess of 4 m b-axis. a- and b-axis ratios are relatively constant throughout the full size range of rafts, sub-components and blocks, with a strong relationship between the two (r^2: 0.80). On the basis of these summary figures, an average block is roughly twice as long as it is wide, with an a-axis of 2.5 m and a b-axis of 1.43 m. This falls well below the threshold raft size described previously, and slightly below the raft sub-component size.

A fraction of a percent of the total block population exhibited a planar depth greater than their planar b-axis. These have not been incorporated in block plots, as in all cases, the blocks were either toppled or appeared to have acquired their form through selective erosion by sheep. It is likely that these blocks had been used as windbreaks for shelter. Block depths fall mainly within the 0.25 - 0.75 m range, with very few blocks exceeding 1.5 m in depth. It is likely that there is some correspondence between peat block c-axis and local peat depth. However, this requires consideration of the spatial distribution of blocks, and is considered in the context of runout in the following chapter.

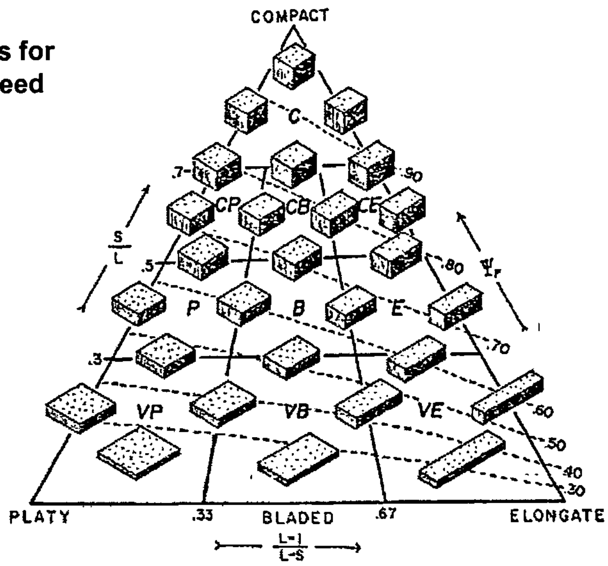
Block shape can be considered with reference to the three principal axes (a, b and c), using a ternary plot, in which ratios of the a, b and c-axes reflect the extent to which particles approximate rods, discs, blades and spheres (Sneed and Folk, 1958; Figure 4.17a). Figure 4.17b shows block shape for all sites, and 4.17c, raft shape for comparison. Broadly speaking, points clustering at the top of each plot are equi-dimensional, and in the case of blocks approximate cubic forms. Those clustering in the bottom right of the plots approximate most closely to rod forms, and those in the bottom left to plates.

Block distribution is widely scattered in the lower half of the summary ternary plot. This suggests that most blocks approximate features that are shallow with respect to their planar dimensions, the major clusters being in the bladed part of the plots. As would be expected, blocks are far more variable in shape than the rafts shown in Figure 4.17c. Rafts are almost exclusively rods and plates. This is unsurprising given the restricted

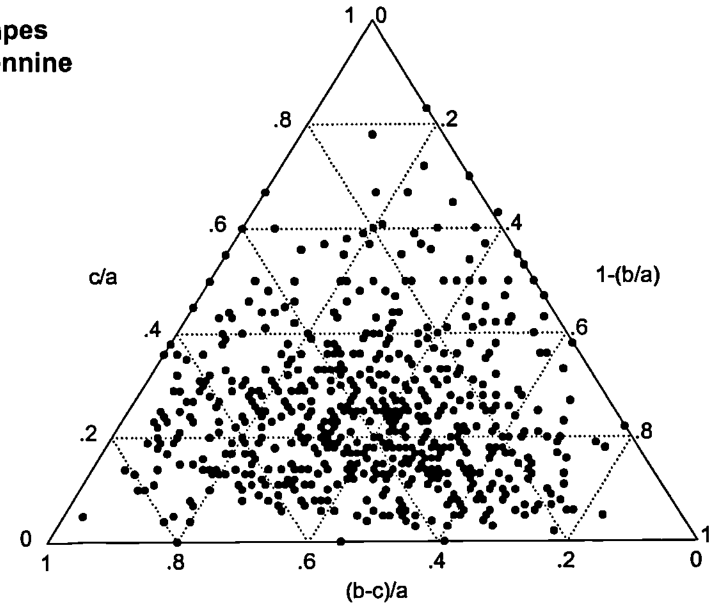
Figure 4.16. a-axes and b-axes square root transformed and separated for rafts, raft sub-components and blocks



a) particle shapes for ternary plots (Sneed and Folk, 1958)



b) block shapes for North Pennine peat slides



c) raft shapes for North Pennine peat slides

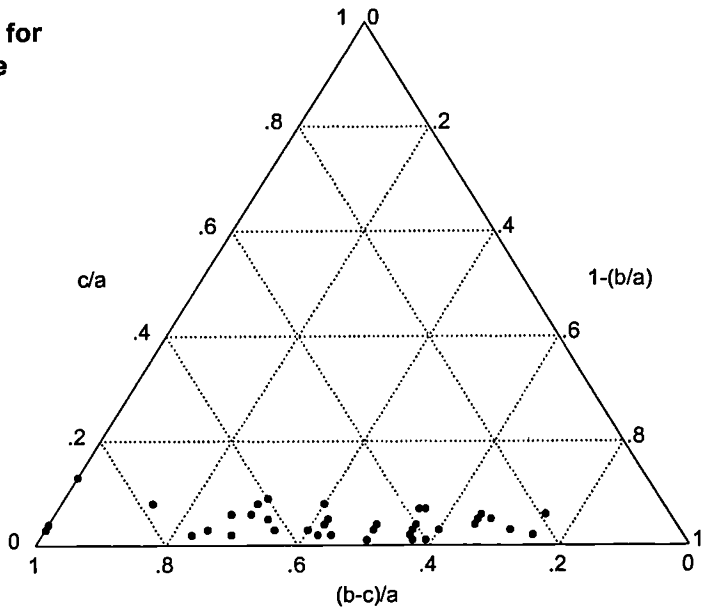


Figure 4.17. Summary plots of raft and block shape for all sites.

c-axes imparted to them by the depths of peat at each site. On this basis, shape would act as a reasonable criterion for distinction of blocks from rafts.

Related to the block shapes, defined by axial ratios, is block roundness. Block roundness may be considered as partly a function of smoothing by weathering, and partly a function of abrasive contacts between blocks during contact. It is not possible to separate the relative importance of weathering and abrasion however. Section 4.1.2 proposed a fourfold division of roundness into angular, sub-angular, sub-rounded and rounded blocks. Summary figures are shown in Table 4.9. Sub-rounded blocks are the most common (23% to 49% from site to site), with rounded and angular blocks providing much of the remainder. If weathering were the dominant control on block roundness, then the small age range covering most of the block sample (1983 - 1995) would explain the consistency in distribution of different shapes across slides. However, ranking of the percentage of angular blocks by age of site does not illustrate an age-roundness relationship, even though block preservation is poorest at the oldest sites. Photographic evidence from both Meldon Hill and Iron Band does not clarify whether blocky deposit was in greater evidence shortly after failure, but Crisp *et al.* (1964) describe its presence. Therefore, it is not possible to ascertain whether the lack of block forms measured at these sites, and Dow Crag, are indicative of abrasion or weathering, or both. The effects of transport in governing roundness are considered in Chapter 5.

Block a-axis orientations are shown in Figure 4.18. Mean orientation and vector strength (a measure of tendency to align in the dominant transport direction) are shown for each plot. Mean orientation is represented by the darker arrow, and the downslope axis of the slide scar by the lighter arrow. Block alignment relates strongly to the downslope axis of the scar in most cases. Middlehope shows the least alignment of blocks, while Nein Head 2, Nein Head 3 and Feldon Burn (with the largest sample sizes) display strong and preferred orientation patterns. The implications of block orientation are best considered with regard to the spatial distribution of blocks, and this is discussed further in Chapter 5.

Block dip is shown in Figure 4.19. Most blocks display shallow tilt of less than 20°, with only a handful of blocks exceeding this. The bladed form of most blocks would preclude significantly greater dip angles. Nein Head 3 shows the largest range of tilts and West Grain the smallest. Assuming toppled blocks display a dip of between 80 and 90°, none of the failures exhibit intact toppled blocks. The overriding tendency towards blocks of low tilt suggests that the intact blocks that *were* measured were

Table 4.9. Summary of block morphometry, morphology and sample sizes for each slide site used in block survey

	Block size						Block shape				Block a-axis orientation		Sampling	
Slide name	Mean a-axis (m)	s.d.	Mean b-axis (m)	s.d.	Mean c-axis (m)	s.d.	% Angular	% Sub-angular	% Sub-rounded	% Rounded	Mean block orientation (deg)	Orientation vector strength	Number of blocks counted	Estimated sampling rate
Benty Hill	2.22	1.50	1.25	0.74	0.45	0.14	8.82	11.76	23.53	55.88	129.5	0.63	68	1:2
Coldcleugh Head	2.16	1.22	1.33	0.56	0.49	0.19	32.26	1.61	33.87	32.26	304.5	0.74	62	1:2
Feldon Burn	2.44	2.32	1.33	0.96	0.445	0.33	8.19	14.04	39.18	27.49	353.2	0.71	171	1:3
Hart Hope	n.d.	n/a	1.17	0.64	n.d.	n/a	n.d	n.d.	n.d.	n.d.	n.d.	n.d.	496	n/a
Iron Band	3.37	1.36	1.74	0.49	0.36	0.18	10.00	50.00	40.00	0.00	286.7	0.90	10	all blocks
Langdon Head	2.99	2.67	1.61	1.03	0.54	0.23	17.33	6.67	36.00	38.67	212.0	0.74	75	1:2
Middlehope	2.86	2.52	1.44	0.84	0.46	0.15	12.90	35.48	48.39	3.23	198.7	0.57	31	1:2
Nein Head 2	2.59	1.40	1.55	0.67	0.54	0.25	20.36	9.58	38.92	31.14	328.9	0.71	167	1:3
Nein Head 3	2.29	0.95	1.39	0.53	0.56	0.19	15.54	7.43	49.32	27.70	0.2	0.715	148	1:3
West Grain	2.64	1.30	1.39	0.68	0.38	0.19	10.00	6.67	40.00	43.33	71.9	0.80	30	1:2

n/a: not applicable
n.d: no data
s.d.: standard deviation

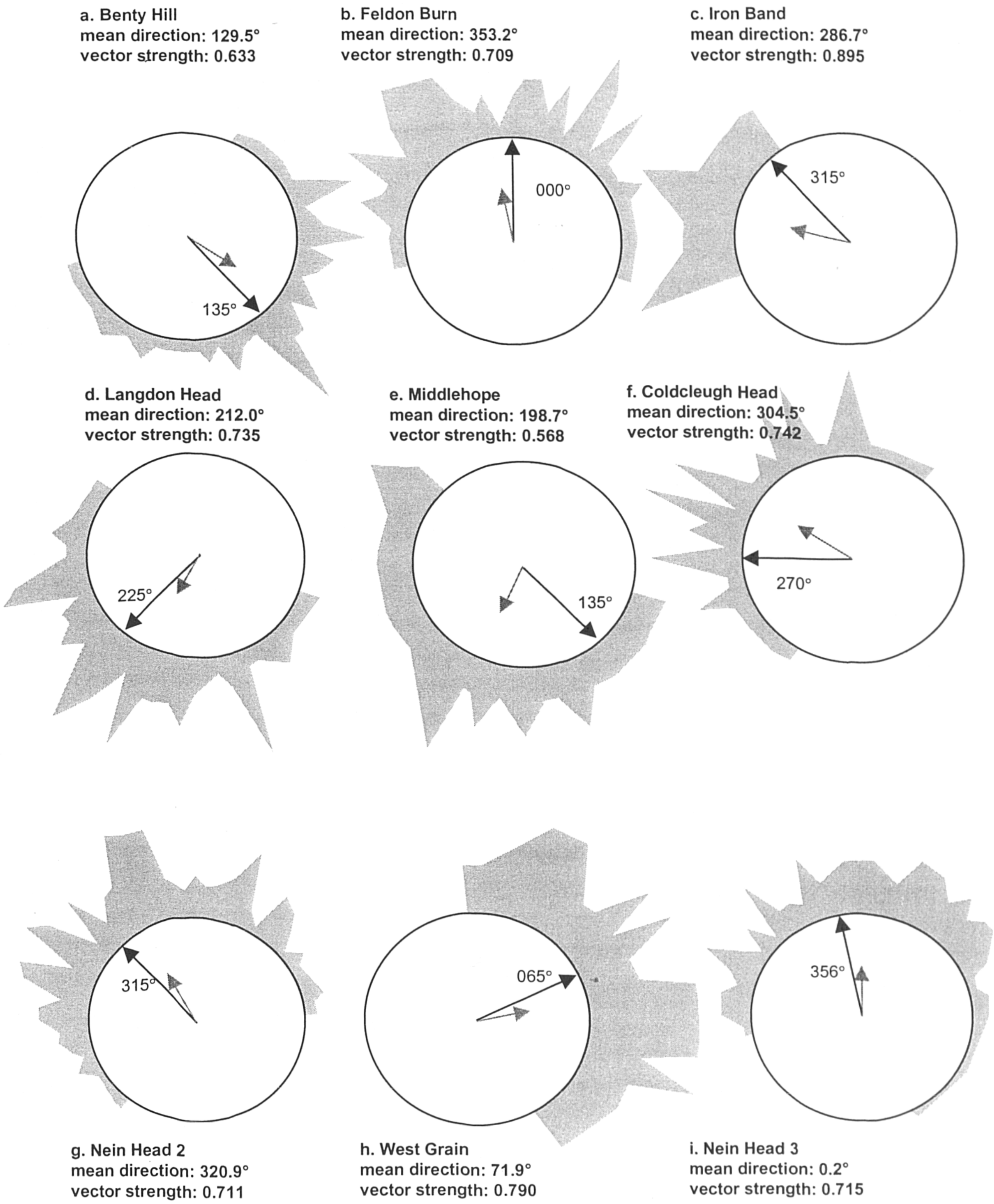


Figure 4.18. Block a-axis orientations for all sites. Shorter arrow shows mean orientation of block population, and labelled arrow shows down-scar major axis

undergoing relatively sedate transport. Block and raft areas do not account for much of the area displaced at slide sites, and hence there is likely to be a significant quantity of debris that may have initiated movement as slabs of peat, but subsequently broke down into forms finer than rafts or blocks. This is likely to be represented by the third form of deposit, slurry. The extent to which deposit is comprised of rafts, blocks and slurry may be significant in relation to the vigour of movement processes between sites.

4.2.6 Slurried deposit

Slurried peat has been observed at recent peat slides in the field (Coldcleugh Head) and in photographs taken shortly after failure (usually a few months, e.g. Nein Head 2 and 3, and Meldon Hill). Figure 4.20 shows photographic evidence of slurried peat deposits. Unlike blocks and rafts, slurry was not visible in slides of five years in age or more. The photographic evidence suggests that slurry is present as a layer of variable depth within the deposit area, and surrounding the blocky deposits. On the basis of typical block depths observed in the field, the photographs would indicate slurry depths between 0.05 m and 0.3 m.

The slurry itself appears from photographs to be a highly remoulded composite of fluidised organic matter and rounded peds of more coherent and intact peat. Dry, weathered slurry observed at Coldcleugh Head appeared more degraded than the available photographs indicated for the Noon Hill and Meldon Hill slides. It is likely that slurry undergoes reasonably rapid structural breakdown in the aftermath of failure. More than twelve months had elapsed since failure at Coldcleugh Head and the first field survey, and it was not considered worthwhile undertaking detailed analysis of slurry structure, given both this assumption and the period of time elapsed since its deposition.

Little information is available as to the distribution of slurry with distance downslope, other than that scar areas appear to remain relatively clear of slurried peat (e.g. Figures 4.9 and 4.10). However, a band of *Juncus* dominated vegetation runs in a band downslope throughout the deposit area, the outer limits of which are concurrent with the maximum lateral displacement of peat blocks. This also appears to be synchronous with the distribution of slurry across the site. *Juncus* is in evidence to a similar extent within blockfields at other sites (Figure 4.21), but never as clearly beyond the scar area, nor in conjunction with recorded field evidence of slurry. Documentary

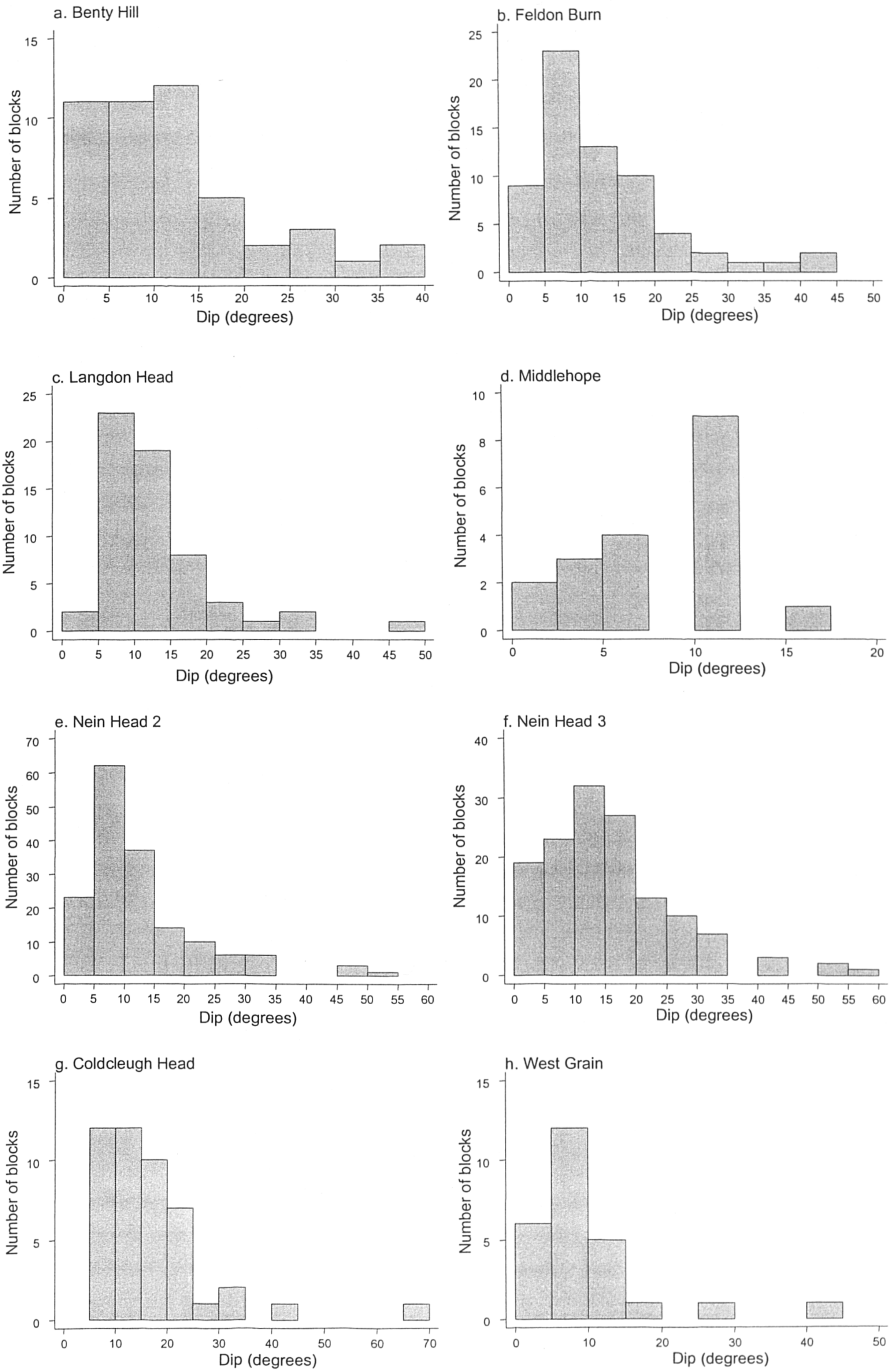


Figure 4.19. Histograms of block dip for all sites

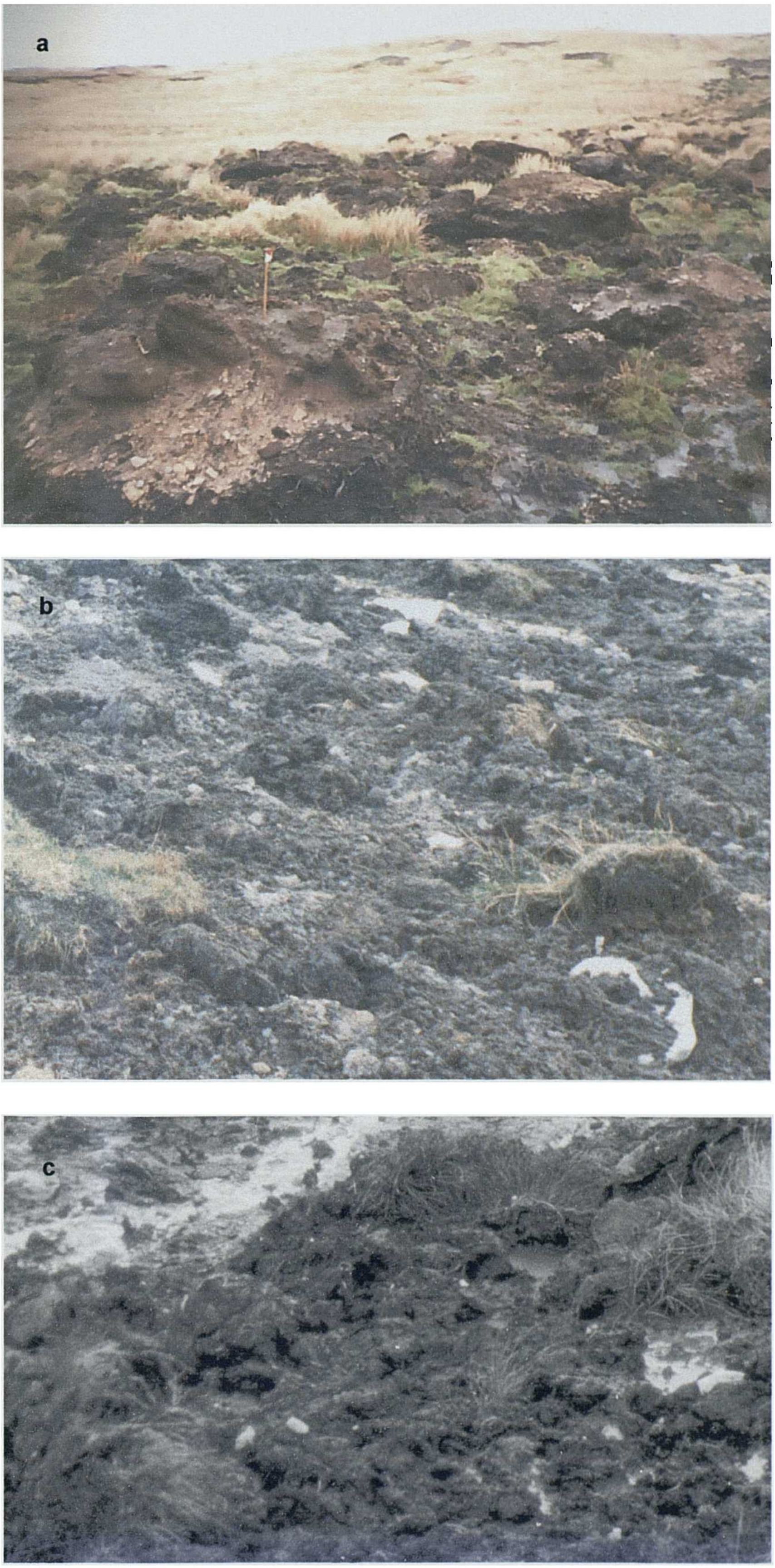


Figure 4.20. Evidence of slurry at peat slide sites: a) Coldcleugh Head - thin film of slurry between larger blocky deposit; b) Nein Head 2 - small peds of peaty debris with substrate showing through on scar surface, former turf block surface in foreground; c) Meldon Hill East - larger peds of peaty debris.

evidence suggests that slurry may be carried significant distances once coupled with drainage networks however (e.g. Archer, 1992; Boyd, 2002).

Chapter 6 considers the material properties of the failed peat mass, and the implications of this for slurry formation during the transport process.

4.2.7 Levees and composite features

Levees are regularly cited as features in rapid mass movements in which the debris has a coarse component (Selby, 1993), e.g. debris flows. Active layer detachment slides in areas of permafrost are similar in form to peat slides, and exhibit debris-flow type failure in which levees are a common feature (Lewkowicz, 1992). Peat 'debris flows' on steep slopes on Campbell Island have been reported as exhibiting levee deposits (Campbell, 1986).

Levee formation at peat slide sites comprises two main types – slurry dominated, and block dominated. In the former, such as at Coldcleugh Head (Figure 4.22a), clear bands of slurried peat are visible bounding the deposit track, but not displaying significant evidence of blocks. The levee forms are slightly raised relative to the non-blocky area of deposit in between. Super-elevated levees are more clearly visible at the Meldon Hill East failure, shown in Figures 4.9 and 4.22b. Again, blocks are sparse to absent. Preservation of such levees seems poor relative to blocks at older sites. It has already been noted that field mapping under-represents deposits at the Meldon slides and at Iron Band. The unconsolidated nature of the slurry is likely to be responsible for its rapid removal by rainsplash and weathering in the aftermath of failure. How extensive these features were at other failures is a matter for speculation.

The second 'levee' type is represented by elevated blocklines, such as at Feldon Burn (Figure 4.22c). Here, blocks are clearly visible in linear arrangements at the deposit margins. They may be more appropriately known as block lines or block trains. Related composite features include block trains within the deposit area, such as those trailing rafts 1 and 7 at Nein Head 2 (Figure 4.6). These may be a product of the break up and settlement of large linear raft deposits, rather than the specific processes likely to be associated with levees. Block jams also occur where blocks pile up locally due to scar surface irregularities or collision with the scar margin. Again, these ideas are further considered in Chapter 5 under runout behaviour.

Figure 4.21. a) *Juncus* filled blockfield at Langdon Head; b) *Juncus* line delimiting area of slurry at Nein Head 3, *Juncus* margin follows outer block limit (block visible next to crouching figure), beyond which are paler grass species (e.g. *Nardus*).

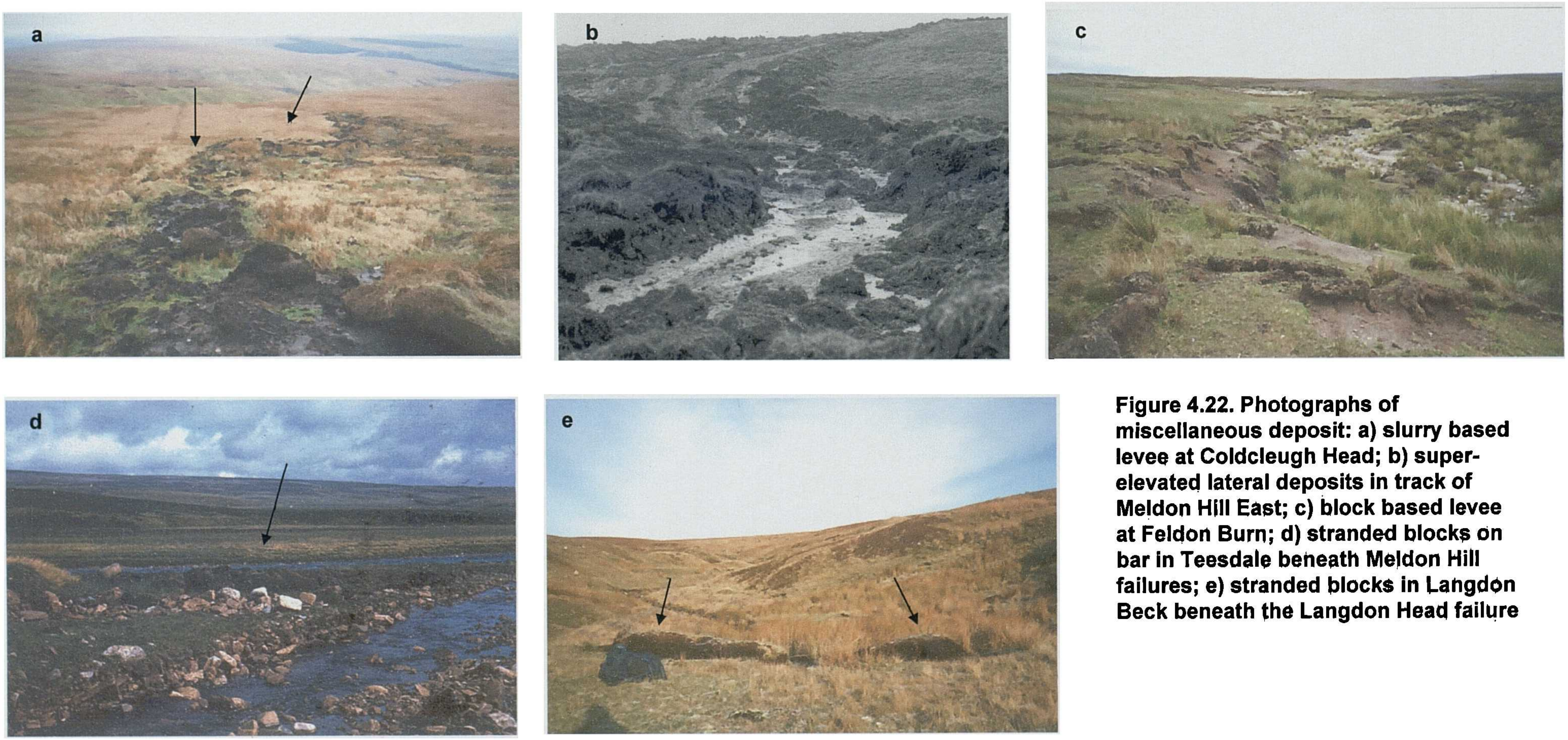


Figure 4.22. Photographs of miscellaneous deposit: a) slurry based levee at Coldcleugh Head; b) super-elevated lateral deposits in track of Meldon Hill East; c) block based levee at Feldon Burn; d) stranded blocks on bar in Teesdale beneath Meldon Hill failures; e) stranded blocks in Langdon Beck beneath the Langdon Head failure

In the lowest reaches of the landscape affected by peat slides, often in capturing gullies and valley bottoms, trashlines of fluidised peat may be observed (Figure 4.22d). These are likely to be a mixture of the slurry discharged during the failure, with water in local streams on coupling, and with isolated blocks, cast out of the flowing mixture during transport. Blocks may be found stranded on channel bars and deposited on channel bank sides during the recession limb of floods associated with the peat slide events. Block remnants are still visible in the streams beneath the Noon Hill slides, Hart Hope and Middlehope, and were recorded on bars on the River Tees by Crisp *et al.* (1964) prior to the building of the Cow Green reservoir (Figures 4.22 e and f).

4.3 Discussion

Several lines of morphological evidence have been described at the North Pennine peat slide sites, which may be related to the aims of the chapter, stated in section 4.0. At the hillslope scale, peat slides in the North Pennines occur in a variety of blanket settings. At one end of the scale, failures initiate near the peat blanket margin, with scars incorporating the transition from peat to mineral soil. At the other, failures initiate near hillslope summits, with scar and deposit contained entirely within the peat. Intermediate failures are described whose deposits break the confines of the peat blanket, either through extension of the deposit zone on land, or through coupling of failure products with local stream networks. These fluvial pathways may extend the influence of peat slides many kilometres beyond their point of origin. In some cases, failures are located within the former paths of existing drainage lines, such as gullies or flushes. This relates to blanket position and the distribution of internal gully networks and external headcutting valley systems.

Associated with this variety of setting is a variability in slope angle and relief. On plateau tops, and valley side benches, slope angles may be as low as 6°. Over steeper slopes, usually associated with deposits, slope angles may be in excess of 25°. This topographic variety is mirrored in the slope forms that underlie the scar and deposit areas. There is no characteristic slope profile form that describes peat slides in the North Pennines, despite the trend of the wider global population established in Chapter 3 (Figure 3.14). Hence, the fifth aim of the chapter cannot be resolved in terms of a hillslope-morphometric classification.

On a site scale, all slides exhibit characteristic juxtaposition of morphological units. These may, for convenience be divided into scar and deposit features. The scars are characteristically highly excavated, and exhibit local evidence of tension in the form of cracks and tears, some of which extend the full depth of the peat mass, and some of which are arranged such that they suggest proto-block formation. This definition of characteristic scar morphology satisfies the fourth aim of the chapter. The deposits reflect their mode of break-up, with large slab-like rafts of material deposited a short distance from their original positions. A sequence of peat blanket break-up from rafts, to blocks, to slurry is proposed, with increasing travel distance favouring increased fragmentation. The justification for this process is based on morphometric criteria, which relate rafts, raft sub-components and blocks. This satisfies the first two aims stated in the introduction to the chapter. It is assumed that below a certain axial ratio of b- and c-axes, blocks may acquire the capacity to tilt and roll, in the process degrading further into slurry. The disaggregated nature of slurry deposit and its absence from most sites at the time of survey prevents further understanding of forms below the block size fraction. Hence, the third aim of the chapter, to establish the significance of slurry has yet to be achieved, and is considered further in Chapter 5.

These assessments of peat slide form can be compared with field surveys in existing studies of peat slides, and of morphologically similar failures in other materials. One of the most detailed interpretations of peat slide morphology was provided by Mitchell (1938) for the Moanbane failure, in Ireland. Mitchell's geomorphological map is redrawn in Figure 4.23a in line with the format of Figures 4.6 to 4.8. Mitchell noted a single large raft, approximately 18 m in diameter, excavated from a granite dominated substrate. The raft was shown on a hillslope profile to have mounted and come to a standstill over the lower scar margin. The scar periphery exhibited extensive cracking, and a distinct upthrust margin. Downslope of this scar and raft were two tongues of debris comprising discrete blocks and smaller levees of slurried peat. It was noted that the blocks remained upright and showed no evidence of rolling, and that they thinned downslope. Mitchell suggested that the presence of more humified lower layers (recorded in a scar stratigraphy) supported block wear during transport, and the generation of slurried peat as a lubricant in the process. He further proposed that more fibrous upper layers were responsible for the arresting of movement with the loss of the humified layers. However, little attempt is made to explain why the failure occurred, or why some parts of the deposit were 'rafted' and some parts more blocky. Mitchell's account shows parallels with the North Pennine slides, and he considers slurry to be entirely a product of the wear of the bases of travelling blocks. He rejects the idea that peat blocks may roll and then degrade. Clarification of this issue requires spatial analysis of block attributes.

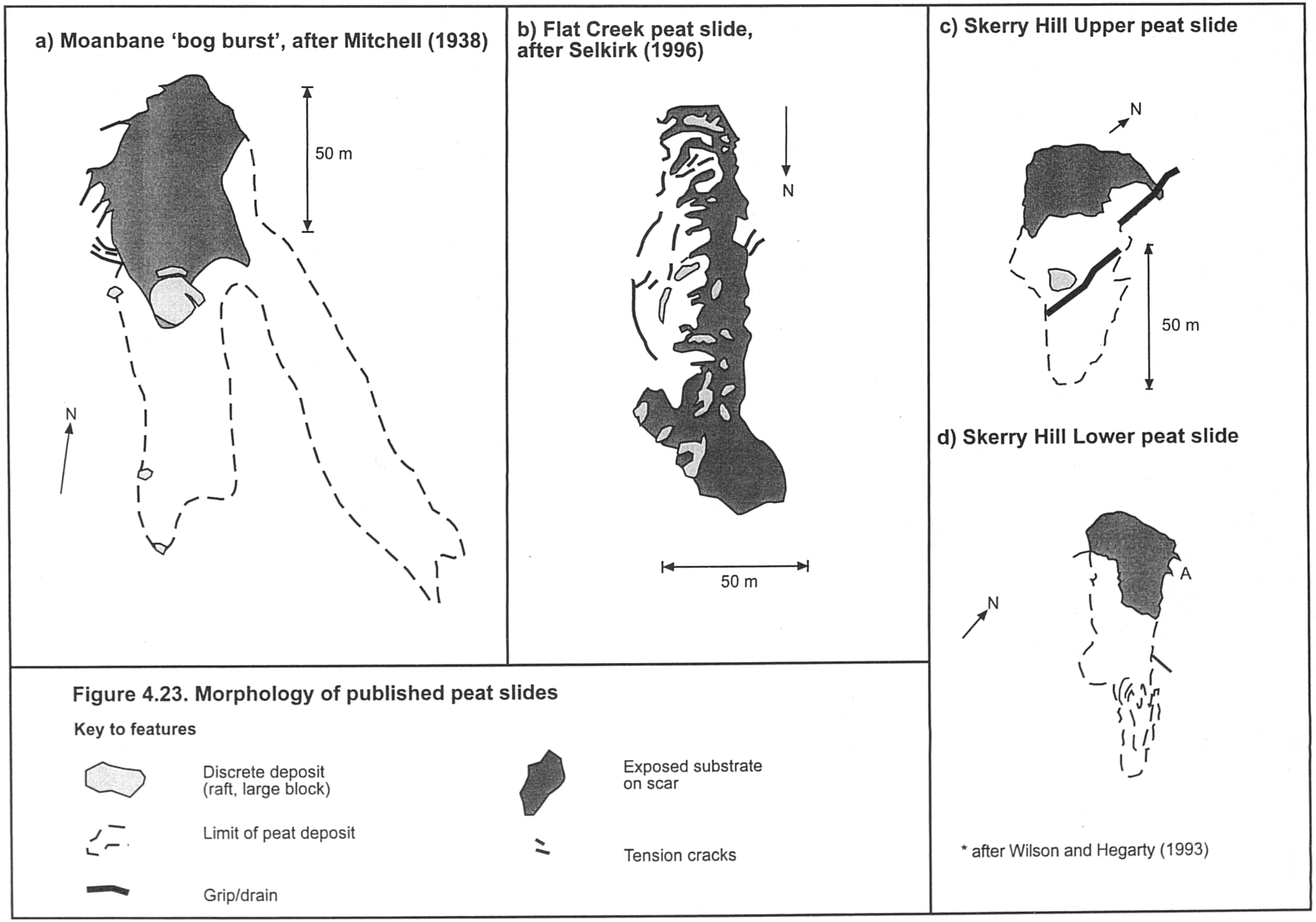


Figure 4.23. Morphology of published peat slides

A more recent report is provided by Wilson and Hegarty (1993) who describe two peat slides on Skerry Hill. Their discussion places similar emphasis on the morphological characteristics of the slides (redrawn in Figures 4.23b and c). However, they provide more detailed assessment of peat material characteristics and climatic antecedents to failure. Rafts and blocks are described, with the largest raft immediately downslope of the scar, underthrusting a drainage ditch and connected peat to produce a 1 m high rampart. Fissures between the blocks are described, but not cracks. Nevertheless, attention to the field maps shows arcuate cracks (A) in the scar margins similar to those mapped by Mitchell. The lower of the two scars exhibits overturned blocks, in combination with peat slurry. They suggest that preservation of the larger peat masses may be a product of undersaturation of the peat.

Other accounts add little to elucidate peat slide morphology. Selkirk (1996) provides limited description and a field map of one of several Macquarie Island failures (Figure 4.23d). She concentrates on the description of ridges and cracks around the scar margins, but ascribes the coherence of several large peat masses to the low slope (approximately 5°) rather than water content. It is clear from these three reports that North Pennine peat slide morphology is consistent with that of peat slides in other locations, but that an understanding of materials and a greater depth of interpretation is required to go beyond the simple assessments of form described.

An example of more detailed consideration of form is provided by the work on active layer slides of Lewkowicz (1990, 1992). Active layer failures are shallow translational landslides that develop over permafrost in response to climatic triggers. Detached active layer material slides or flows downslope over a failure surface parallel to the pre-existing topography, resulting in a bare scar zone, a track containing isolated blocks, and a depositional area where the main part of the slide ceases movement (Harris and Lewkowicz, 1993). Scar depths average around 0.6 m, and block diameters between 0.5 and 1.0 m. Upthrust scar margins result where the rafts of failed material force their way through constrictions. This description is very close to that of peat slides, and photographs of the features heighten this sense of similarity. Harris and Lewkowicz (1993) used distinctive sand, gravel and organic layers to map the distribution of compressive and extensional forces throughout active layer slide extents, by digging sections into each morphological unit. This revealed extensive folding and buckling at points where transported material contacted other static material. The shear zone at the base of the rafts and blocks was described as between 1 or 2 mm and several centimetres in thickness. This parallels the uncertainty over the location of the failure plane in peat slides. It also highlights the value in undertaking studies of failed materials in order to further understand the mechanics of their behaviour in transport and deposition.

Figure 4.24 provides a morphological conceptual model of peat slide form based on the previous summaries. A 'typical' peat slide failure is characterised initially by two major morphological components. Over the shallower gradients of upper valley slopes, peat is excavated from the substrate beneath, leaving a partial to complete crescent scar (e.g. Meldon Hill East and West, Iron Band, Langdon Beck, Nein Head 3). Scar shape tends towards elongate and linear dimensions where the peat slide occupies a former drainage line (e.g. Feldon Burn, Hart Hope), and towards broader rectangular dimensions otherwise (e.g. Middlehope, Langdon Head). The upper scar margin is disrupted by tension features which may adjoin it, or be offset and parallel-to-oblique to the margin. Where indicative of tension at the surface only, these may be manifest as shallow tears, widest at their midpoints and tapering distally. Where tension has been experienced throughout the profile depth, they are manifest as cracks, which are narrow, less distinct at the surface and deeper.

The first point at which relatively intact peat is deposited marks the onset of the raft field. This may be very close to the scar head where excavation is minimal (e.g. Hart Hope, Langdon Head) or further away (e.g. Nein Head 2 and Nein Head 3). Rafting is generally confined to the shallower angles of the upper slopes, with raft size declining rapidly over convex breaks of slope. The presence of significant numbers of blocks or areas of slurry normally indicates a transition from rafting as the major form of transport to smaller scale transport. The raft, block and slurry fields always overlap to some extent, as raft break-up involves the generation of these latter forms.

The slurry field is normally defined by the presence of blocks, which delimit its margins and distal limits. The distinction between components of the raft and block field may be ambiguous. However, once the sub-components (or limbs) of major rafts become independent from one another, they tend more towards blocks than rafts. Blocks are distinguished from rafts by their small size, and by their ability to tilt around their a- and b-axes. This may result in a seemingly chaotic jumble of peat blocks throughout the scar area. With increasing distance of blocks from the scar head, an overall fining effect results. Ultimately, finer 'peds' of peat derived from broken blocks form part of the slurry field. Other than extent, little further information is available as to the nature of the slurry field. Both it, and the block field may connect with local drainage networks, where transport is water assisted, and where sedimentary evidence is rapidly lost.

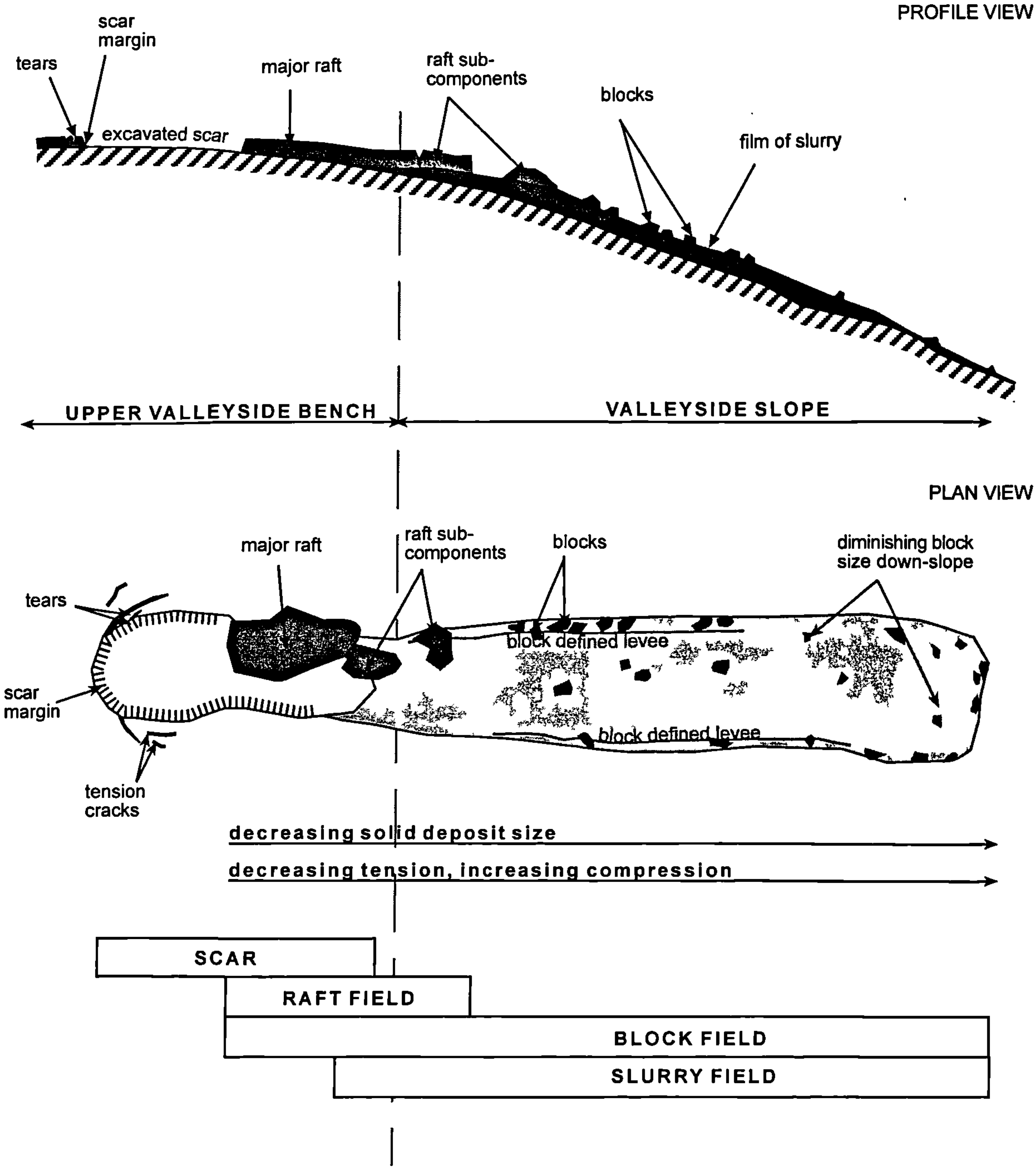


Figure 4.24. Morphological conceptual model for peat slide sites.

Profile and plan views illustrate key morphological components. Slope context illustrates position of solid deposit relative to major slope breaks. Broad zonation illustrated by zone bars at bottom.

The justification for this model is considered further in the following chapters, on the basis of spatial distribution of deposits, reconstructed sediment budgets and material characteristics of the failing peat mass. A process-based model is then formulated, explaining the distribution of these forms.

5. PEAT SLIDE SEDIMENT DYNAMICS

5.0 Introduction

The previous chapter demonstrated that peat slides exhibit characteristic and diagnostic morphology within their scar areas and deposit. This chapter examines the spatial distribution of debris and deposit attributes (size, shape, arrangement) and attempts to determine the processes responsible. In the absence of direct evidence, inference from sedimentary deposits provides the best indication of process activity. The dimensions of rafted debris are such that they cannot physically be transported, other than by sliding (section 4.3). The dimensions of blocky deposits are more variable, and in many cases, the blocks approximate spindle forms of equivalent b- and c-axes. These may roll as well as slide (section 4.3). Rolling transport may subject more of the peat block to stress, and perhaps accelerate wear in transport. It is suggested that this is one of the origins of the sub-block slurry deposit described in section 4.2.6.

The objectives of this chapter are to establish the nature of transport and modification of debris. These objectives may be formalized in the following aims:

i) to characterize the spatial distribution of the three major deposit types - rafts, blocks and slurry, and to establish their relative significance within the slide area;

ii) to establish if changes in the size of deposit relates to transport distance;

iii) to identify modes of transport for the block sediment fraction;

iv) to establish sediment budgets of the peat slide events.

Assuming the scar head is the origin of the mass movement, clearly identifiable at all slide sites using raft and block data (section 4.2.5), the following hypotheses can be tested.

Firstly, that overall solid deposit dimensions will decline with increasing distance downslope. In so doing, the relative significance of rafts, blocks and slurry will change as a percentage of the total volume of debris in any one location. The second hypothesis follows, that the percentage of rafts and blocks will decrease downslope, and that the percentage of slurried deposit will increase downslope. Both of these hypotheses are tested by mapping the spatial extent of each deposit type across the full range of North Pennine slides, and through the construction of event sediment budgets that subdivide the debris by deposit type (rafts, blocks and slurry).

The third hypothesis relates to the dynamics of deposition. It proposes that patterns of sedimentation indicate variations in the nature and extent of process activity. In the case of translational sliding, this will be evident in peat rafts and blocks where [peat] turf surfaces align parallel to the underlying topography. There may also be common alignment of the long-axes of blocks if process activity is minimal subsequent to larger mass break-up. In the case of more vigorous movement, such as flowing or rolling, involving multiple impacts and fragmentation, the solid deposits will exhibit chaotic dip of turf surfaces, and random long-axis alignment.

The following sections describe the methodology employed in quantifying the spatial distribution of deposits, in interpretation of the arrangement of deposit constituents, and in construction of sediment budgets for each peat slide. Analysis and discussion follows.

5.1 Methodology

The data sets presented in this chapter are derived from field validated measures of deposit type (raft, block, slurry), character (dimensions) and extent (position, setting). The following sections consider the analytical methods for block volume, orientation and dip, then a zonal analysis of spatially dependent block characteristics, and finally sediment budgets for the peat slide events as a whole. Chapter 7 considers sediment budgets for geomorphic activity in the aftermath of failure.

Block analyses were carried out in full at Benty Hill, Coldcleugh Head, Feldon Burn, Langdon Head, Middlehope, Nein Head 2, Nein Head 3 and West Grain. Prior block study at Hart Hope (Warburton *et al.*, in press) was not replicated in this thesis, particularly given the size and complexity of the site, though results from that work are commented upon here. At the four sites experiencing failure in the 1960s, block work was not undertaken for differing reasons. At the Meldon Hill slides (1963), block weathering had progressed to the point where it was not possible to distinguish between blocks and hummocks in the deposit. Although this is also the case at the Iron Band (1964) failure, some blocks were still visible. The small sample population here (approximately 14) was regarded as insufficient for quantitative analysis to be undertaken. At the Langdon Beck (1961) failure, the morphology was extremely simple, and only two blocks were found within the scar area. The ground immediately beneath the failure consisted primarily of mine works of steep relief, which may rapidly have had their deposits reworked. The remaining failure at Dow Crag (1930) exhibited several vague block forms, but again uncertainty as to their origin, degree of weathering and the total number of blocks prevented further attempts in their quantitative analysis.

5.1.1 Spatial analysis of block distribution by mapping

Six types of block map were constructed from field surveys of block position using a Total Station, and using the block attributes measured for the surveyed blocks. Maps were constructed to enable analysis of block size and shape, vectorial information such as long axis orientation and dip, and morphological information including length/width ratios, block depths and gross three dimensional hillslope profiles. These maps are as follows:

i) **Block volume maps:** for each block surveyed in the field, approximate block volume was calculated as a product of the a-, b- and c-axes in cubic metres. Block volumes were mapped using a proportional circle plotted over the centre, on a geomorphological map (presented earlier in Chapter 4). Hence, a block of 10 m^3 in volume would have a proportional circle twice the area of a block 5 m^3 in volume. Blocks were solid-fill colour coded according to roundness, with red representing angular blocks, orange sub-angular blocks, yellow sub-rounded blocks and green, rounded blocks. In order that the maps be interpretable on paper of a practicable size, circle sizes were determined individually by site according to the range of sizes present and the scale of the site. This prevents direct comparison of blocks between sites without attention to the scale but permits better visual interpretation of patterns. A consequence of the variable scaling is overlap of blocks (most notably at Langdon Head and Nein Head 2, the largest and most rafted of failures). Where this is the case, smaller blocks are shown overlaying the larger blocks. No blocks are entirely concealed by other blocks on any of the maps, and where blocks obscure important detail in the geomorphological maps, they are represented by outlines only, in the colour corresponding to their roundness. This was only necessary at the Langdon Head site.

ii) **Block orientation maps:** retaining the block volumes from the previous maps, long-axis orientations were centred over each block using a line of uniform length and thickness. No vector weighting is attached to the lines on the basis of length/width ratio or other measure of magnitude. This reflects the relatively consistent length/width ratios reported in section 4.2.5.2.

iii) **Block dip maps:** dip values were plotted over the centre of each block. Unlike orientation, dip was logged in the field according to the dip aspect and degree of dip (see Table 4.3). Dip aspect was represented by an arrow pointing in the direction of dip, and scaled linearly with the degree of dip. For example, a long arrow pointing down-slope would represent a block maximum projection plane tilting forward (or dipping down-slope) at a relatively high angle. A short arrow pointing upslope would represent a very low tilt (or dip) such that the maximum projection plane would be backtilted.

iv) **Block depth maps:** block depth maps were constructed using proportional circles on the same basis as the block volume maps, except substituting block depths for block volumes.

v) **Block length/width maps:** length/width ratios were plotted on the same principles as those used to produce volume maps, but with length/width ratios scaled between 0 and 1 cm for the full range of ratios at individual sites. This enabled direct comparison of maxima and minima between sites. This also had the effect of reducing the visual significance of low ratio blocks, with low orientation potential.

vi) **Three dimensional hillslope profiles:** contour plots of altitude at 5 m intervals, using the Contour facility in SURFER v6.01, were constructed using all spatial data taken during the baseline Total Station field surveys. These were used as an aid in interpretation of the previous set of maps, and provided a higher resolution topographic representation of each site than afforded by Ordnance Survey maps.

5.1.2 Spatial analysis of block distribution by zone

To provide a more rigorous assessment of spatial arrangement of block attributes, block data types were referenced to three variables: topography, runout distance and position within larger deposit zones (such as levees or discrete lobes). Runout distances of all blocks were referenced to a common point at all slides, the upslope limit of the headscar. Furthermore, given increasing runout distances, block characteristics were considered more likely to be dependent on transport processes rather than processes governing their initial separation from the intact blanket. There are conceptual difficulties associated with using the scar head as the origin, as all blocks cannot start from the same point. However, the use of other physically based reference points such as the centroid of the failed or deposited masses would introduce negative travel distances for some of the block population rendering much of the analysis nonsensical.

In order to achieve a satisfactory sample of blocks from top to bottom of the failure, the total disturbance distance (from top of the headscar to lower un-channelised limit of the deposit) was subdivided into ground slope deposit zones of 30 m in length[1]. This provided a good balance between the number of zones, and the number of blocks per zone. It also corresponded well to the resolution of hillslope transects described in Chapter 4. Mean slope angles of each zone were used to group blocks by slope angle, having the effect of sorting blocks by the topography over which they were deposited, but ignoring the effects of inheritance. Figure 5.1 illustrates the differing way in which blocks were grouped for analysis, and Table 5.1 gives details of the sampling framework.

Blocks were classified according to several characteristic morphological units, derived from subjective interpretation of deposit arrangement. Morphological units were defined as follows:

a) terminal lobe:	end of deposit track
b) non-terminal block jam:	block jam within track
c) terminal block jam:	block jam acting as secondary terminus (not terminal lobe)
d) channelised:	topographically confined blocks
e) diverted:	blocks diverted by obstruction from other blocks
f) free-flow:	non-terminal, non-obstructed, non-diverted blocks
g) marginal:	the most marginal blocks on the deposit track
h) scar-stranded:	isolated blocks stranded on the scar

[1] At Nein Head 2, zone lengths were 30 m and 60 m, given the failure length. 60 m zone lengths were used in the final analysis.

Figure 5.1. Block groupings for sediment dynamics analysis: a) block grouping by 30 m deposit zone; b) block grouping by common slope angle range within 30 m deposit zones; c) block grouping by morphological context

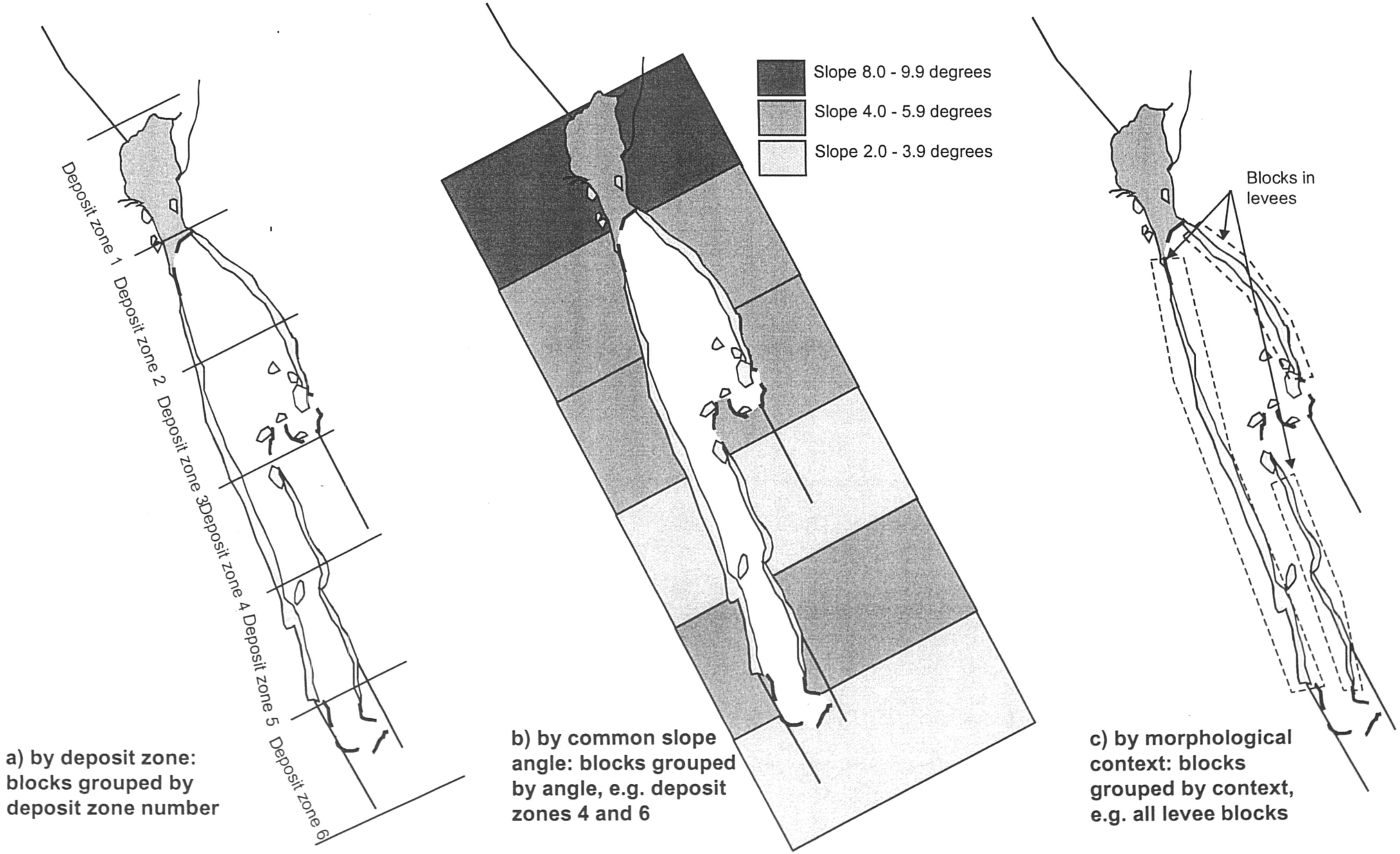


Table 5.1. Deposit zone details for sites in block analysis and sediment budgets

Site	Number of zones	Total block sample	Maximum number of blocks per zone	Minimum number of blocks per zone	Mean number of blocks per zone	Number of 'dead**' zones
Benty Hill	12	63	14	1	5.3	0
Coldcleugh Head	8	62	18	2	7.8	0
Feldon Burn	12	70	11	1	5.8	0
Langdon Head	14	59	11	0	5.4	3
Middlehope	7	27	6	1	3.9	0
Nein Head 2*	14	154	27	3	11	0
Nein Head 3	16	99	14	0	6.6	1
West Grain	8	29	11	0	4.1	1

* at 60 m zone resolution

** a dead zone contains no blocks, and hence is excluded from zonal analysis

Table 5.2. Slope-channel coupling status of North Pennine peat slides

Site	Slope-channel coupled at time of failure	Stream order of receiving channel	Catchment
Benty Hill	yes	1	South Tyne
Coldcleugh Head	no	-	South Tyne
Dow Crag	yes	1	Eden
Feldon Burn	yes		Derwent
Hart Hope	yes	2	Tees
Iron Band	yes	2	Eden
Langdon Beck	no	-	Tees
Langdon Head	yes	1	Tees
Meldon Hill East	yes	1	Tees
Meldon Hill West	yes	1	Tees
Middlehope	yes	1	Wear
Nein Head 2	yes	1	Wear
Nein Head 3	no	-	Wear
West Grain	no	-	Wear

5.1.3 Calculation of event sediment budgets

Event sediment budgets were constructed for each failure describing the movement of sediment during the main peat slide 'event'. Subsequent washing away of loose debris was not incorporated in the 'event' budget, but is discussed in Chapter 7 in the context of slide site evolution. The budgets incorporate assessment of the amount of material mobilised, the amount of material deposited, and the amount of material delivered to local channel networks. Figure 5.1c illustrates a schematic of the sediment budget calculations.

i) **Sediment mobilised:** using the 30 m zones described previously, each zone scar area was multiplied by peat blanket depth, derived from the cores taken at the scar margins (described in Chapter 6), and providing a volume in m^3 of sediment mobilized. These peat depths were felt to be more accurate than raft or block depths, which may have changed due to abrasion and shrinkage. This was converted to mass using a bulk density of 1 t m^{-3} of peat, a value within the narrow range for bog peats described in Chapter 2 and sampled for North Pennine slides in Chapter 6.

ii) **Sediment deposited:** the three deposit types were considered separately on a zone by zone basis. Raft volumes were calculated by summing the area of rafts per zone and multiplying by the appropriate cored depths (as with the 'sediment mobilised' method). Total block volumes per zone were calculated as a sum of all individual products of a-, b- and c-axes, with the total measured block volume per zone multiplied by a block sampling scaling ratio. For example, sites at which 1 in 3 blocks were sampled, had block volumes upscaled by three times.

For the purposes of sites where sediment was undelivered to local stream networks, the 'slurried' volume of the deposit was assumed to be equivalent to the total volume displaced, less the solid component (rafts and blocks). Field observations, and comparison with photographs taken shortly after some of the events suggest that a relatively even film of slurry accompanies much of the blockfields left as deposit. The calculated slurry volume was distributed by zone over the area delimited by the blockfield in each slide. This was done on the basis that slurry would be found throughout the deposit area, and in broadly equivalent depths from zone to zone.

In the case of failures coupled to local fluvial networks, sediment delivered was calculated as an additional component of sedimentary activity. Failures discharged directly onto existing watercourses (as at Langdon Head or Feldon Burn), or via gullies coupled at the base of their scar areas (e.g. Hart Hope). Table 5.2 shows the coupling relationships of all failures considered in the sediment budget analysis. Calculations were as follows:

iii) **Sediment delivered:** sediment delivered was calculated as all the sediment not accounted for by either rafts, blocks or slurry. An arbitrary uniform slurry depth was applied over the full extent of the uncoupled deposit track. This depth was derived from uncoupled sites, with good solid deposit preservation (Nein Head 3, West Grain and Coldcleugh Head) for which slurry volumes could be calculated. A range of between 0.7 and 0.21 m slurry depth was calculated for these sites, and the mean of 0.12 m was used as an approximation of the slurry depth for all other sites.

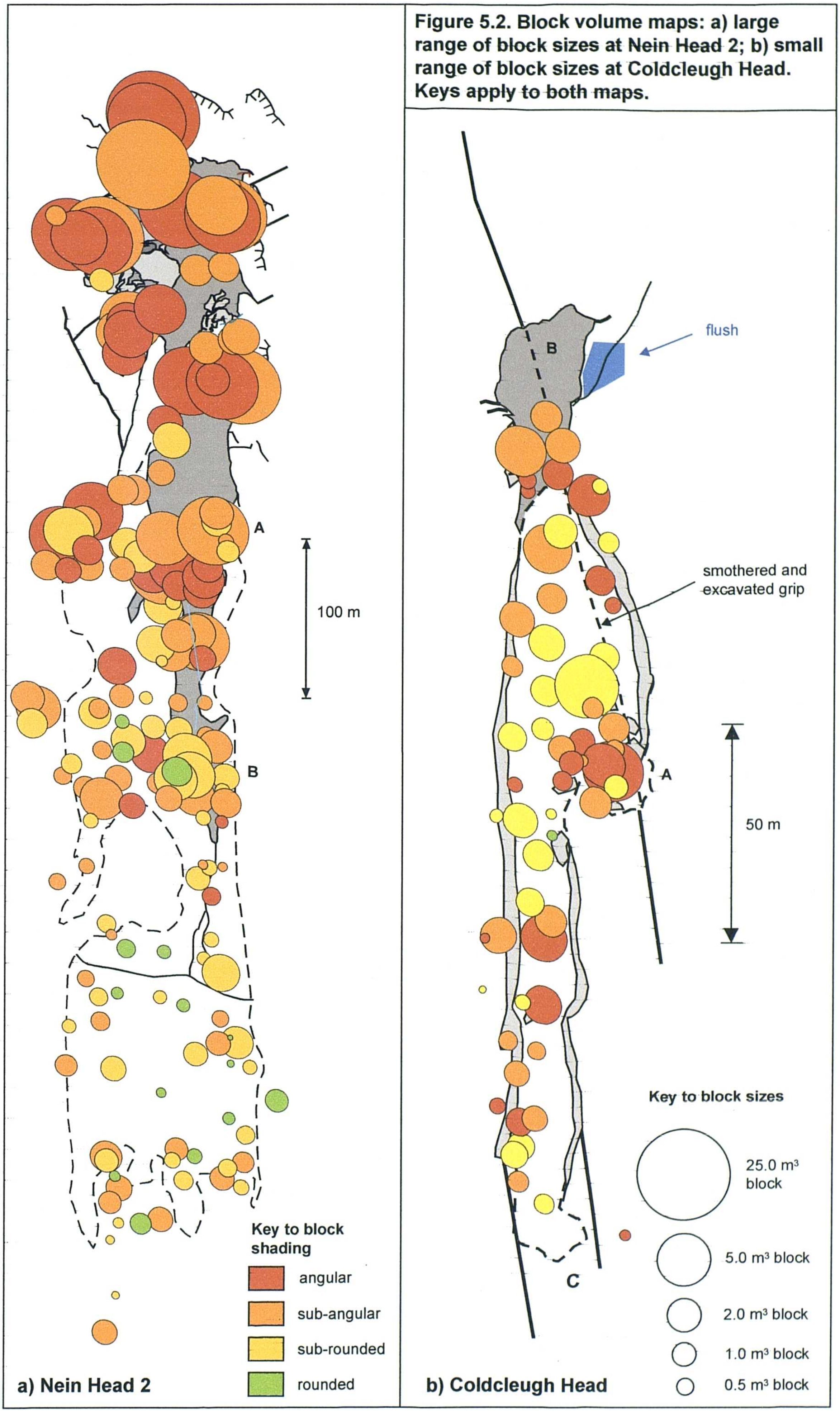
In all cases, area calculations were performed on survey-calibrated aerial photographs. A pixel based measurement program, SigmaScan v1.20, was used to count the number of pixels comprising scar, raft and slurry area in each zone, according to the maps produced in Chapter 4. Constructing the sediment budget on the basis of zones allowed the comparison of downslope trends in sedimentation patterns.

5.2 Results

5.2.1 Mapping of block volume and block smoothing

Figures 5.2a and b show examples of two block volume maps at Nein Head 2 and Coldcleugh Head. In the former slide, block volumes vary widely from top to bottom of the feature, while at the latter, block volumes are far more uniform. Block volume variability is greatest at Nein Head 2, Langdon Head and Benty Hill, and lowest at Coldcleugh Head and West Grain (Table 5.3). In the case of the former sites, Nein Head 2 and Benty Hill exhibit clear decreases in mean block volume down-slope. A similar decline is visible at the other sites, but is less clear. In the cases of large block volume variability, the largest blocks (between 5 and 15 m^3) are found slightly down-slope of heavily rafted sections, and are probably associated with raft breakup. Coincidentally, these rafted areas (described in section 4.2.5.1) are also of relatively low slope angle (between 3° and 4° in the plateau sections of both Benty Hill and Nein Head 2). On the rectilinear slopes (West Grain, Coldcleugh Head, Feldon Burn) down-slope decrease in block size is less obvious. The smallest blocks (< 1 m^3) are found scattered in the central areas of the runout zones.

Figure 5.2. Block volume maps: a) large range of block sizes at Nein Head 2; b) small range of block sizes at Coldcleugh Head. Keys apply to both maps.



In the larger failures in which coupling is immediate and blocks enter channels rather than form zones of runout, lateral levees may be visible (e.g. Meldon Hill, Figure 4.9a; Iron Band, Figure 4.10). Alternatively, most of the preserved blocks may be confined within the scars themselves (such as at Langdon Head and Middlehope). The slides which are not coupled runout over the undisturbed peat blanket. Blocks exit the scar and spread out, where the peat at the scar margin thins and where the scar pinches out (e.g. Nein Head 2, Nein Head 3). Block density is relatively even throughout the deposit area. In these latter failures, there is little evidence of concentration in block numbers at margins that might be associated with levees. Some sites do exhibit local peaks in density, and the implications of these patterns of clustering are considered next.

Both Nein Head failures exhibit bands of high and low block density from top to bottom of each failure. At Nein Head 2, these are located in the middle and lower parts of the lower scar, marked A and B (see Figure 5.2a), while at Nein Head 3, the first cluster is located within the main scar, with three evenly spaced clusters throughout the runout zone downslope. This clustering may relate to alternating zones of local compression in high density parts of the track and zones of extension in the lower density parts of the track. The similarity in clustering may relate to similar slope controls, as the slides are adjacent to one another on the north face of Noon Hill.

At Coldcleugh Head, a major block jam occurs on the left side of the track, with a second extended lobe diverted around this jam to extend to the slide terminus. This two-stage deposition process is more clearly visible on the aerial photograph in Figure 5.3. The primary lobe (A) consists of larger blocks that have followed the line of the grip (shown on Figure 5.2b, and concealed in Figure 5.3) and formed a barrier to the subsequent failed material, sliding from a flushed area at B. This material has been diverted around the primary lobe, and being wetter has broken down into a more slurried track that extends to the terminus of the deposit (C).

Of the remaining slides, block distributions provide little clear evidence of movement patterns, though distinct blocky lobes broken away from raft fronts are visible at Benty Hill (Figure 5.4b, marked A and B) beneath the main rafted area. Nein Head 3 appears to show a complex pattern of jamming and diversion in the track. Where blocks are channelised by existing drainage features (such as gullies), deposit tracks become more linear, with blocks confined within the walls of the gully (e.g. Benty Hill), or superelevated in block lines at their outer limits (Feldon Burn: Figure 5.4a). In some cases (e.g.

Table 5.3. Summary statistics for block characteristics by zone, including block counts, block roundness, mean block orientation and block size

Site name	Number of blocks	Mean block volume (m^3)	Block volume standard deviation	% angular	% sub-angular	% sub-rounded	% rounded	Mean block orientation (degrees)	Main slope aspect (degrees)
Benty Hill	63	1.8	2.9	8.8	23.5	55.9	11.8	129.5	140
Coldcleugh Head	62	1.6	1.8	32.3	33.9	32.3	1.6	304.5	250
Feldon Burn	70	6.3	8.0	9.3	44.4	30.9	15.4	353.2	000
Langdon Head	59	4.0	6.7	17.6	37.8	39.2	5.4	212.0	220
Middlehope	27	2.9	4.3	16.1	35.5	48.4	0.0	198.7	140
Nein Head 2	154	3.1	4.3	20.2	38.7	31.5	9.5	328.9	320
Nein Head 3	99	2.4	4.1	16.2	49.3	27.7	6.8	0.2	000
West Grain	29	1.9	2.3	10.3	37.9	44.8	6.9	71.9	020

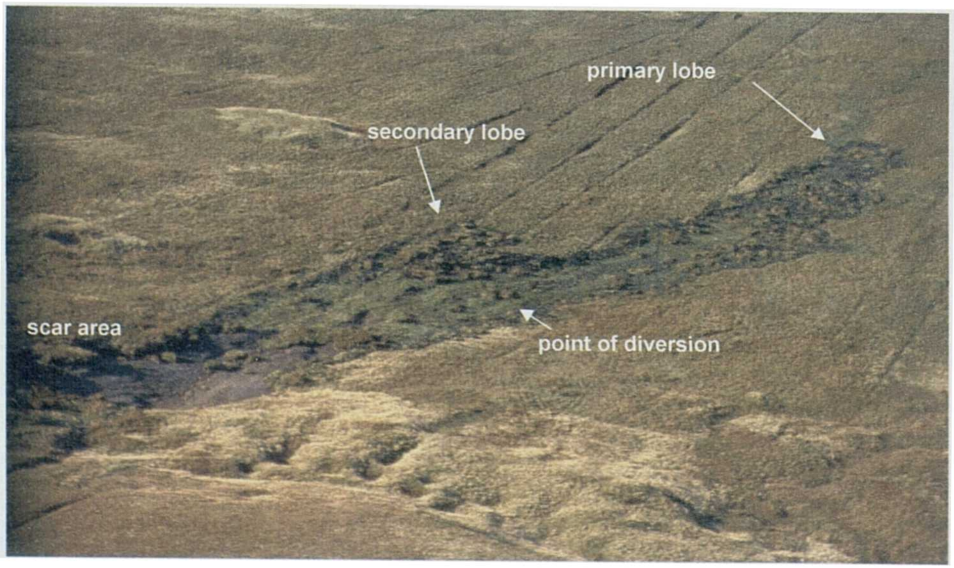


Figure 5.3. Coldcleugh Head lobes and point of diversion. The most coherent mass of larger blocks comes to a halt in the primary lobe, around which are diverted the remaining blocks. The slurry path is highlighted by the darker green matted bog vegetation. Blocks are clustered on the right bank of the lower track.

Middlehope, Langdon Head), coupling means that most of the preserved blocks are found stranded on the scar, as there is no runout zone beyond it. These blocks are often isolated, and cannot be distinctly related to the transport processes of other blocks.

Block rounding is variable across slides (Table 5.3). The majority of blocks are either sub-rounded or sub-angular (between 60 and 80%), with angular blocks infrequent (between 8 and 30%) and generally concentrated in the upper parts of slide scars. Rounded blocks are very infrequent (0 to 15%), and concentrate more in the lower reaches of slide tracks. Again, some sites show patterning in block angularity, whilst in others there is little apparent spatial control.

At Nein Head 2 (Figure 5.2a), angular blocks comprise many of the blocks of larger volume in the upper scar, with rounding increasing down-slope, particularly as block sizes decrease over the break of slope beneath the terminus of the lower scar. Rounded blocks begin to appear in the lower parts of the lower scar and increase in number towards the toe of the slide. Such patterns are not visible at Nein Head 3, where angular blocks occupy a wide range of sizes and are found throughout the feature length. Angular blocks are far less frequent at other sites, although they are clustered on the left bank margin and in the block jam at Coldcleugh Head (Figure 5.2b).

5.2.2 Mapping of block orientations

Typical block orientation patterns are shown plotted for Feldon Burn and Benty Hill in Figure 5.4. They exhibit both zones of preferred orientation and extensive areas in which orientation appears to be random. For example, at Feldon Burn, block long axis orientation appears aligned with direction of transport within the highlighted central channelised section beneath the scar confluence. Super-elevated blocks cast beyond the channel (and pictured in Figure 4.22, Chapter 4) are aligned oblique to the transport direction. At Benty Hill, the two adjacent block lobes described in the previous section, despite occurring over equivalent slope long profiles, exhibit contrasting orientation patterns. The left bank side lobe shows alignment of blocks in the direction of transport, while the right hand side lobe exhibits uniformly oblique orientations, with terminal blocks normal to the down-slope axis. Both failures show blocks oriented parallel to local scar aspects in the scar head areas.

Examination of the eight block maps suggest consistency in block arrangement according

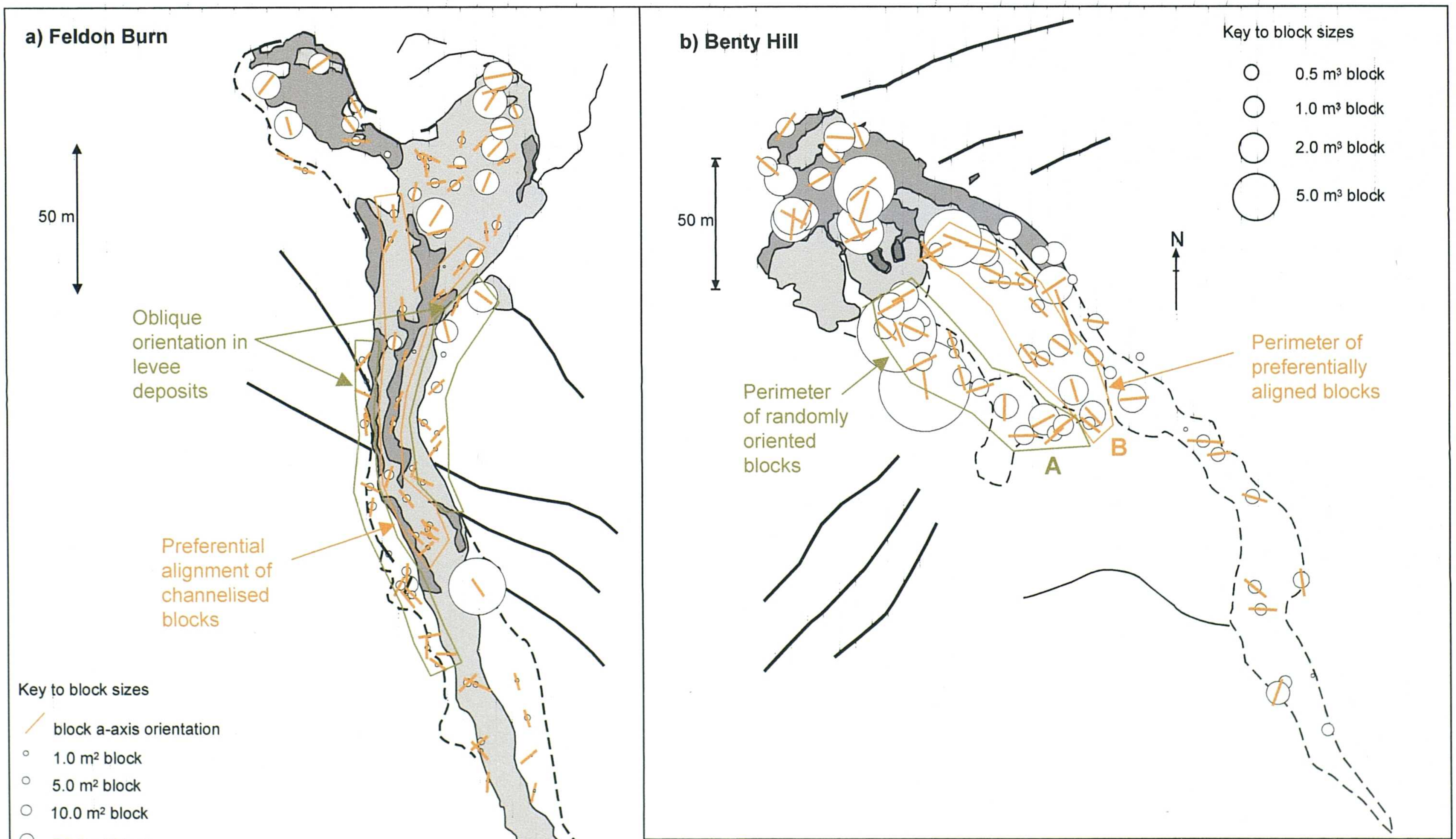


Figure 5.4. Block orientation maps; a) preferred orientation in channels and levees at Feldon Burn, b) randomly orientated blocks at Benty Hill adjacent to preferentially orientated blocks in two block lobes over plateau. Equal line lengths used for all blocks. Keys apply to both maps.

Terminal block jam (left bank side of Coldcleugh Head)

Marginal (right bank side of Feldon Burn)

Non terminal block jam (middle of lower scar of Nein Head 2)

Terminal lobe (right bank side of Nein Head 3)

Free flowing (lower deposit track of Nein Head 2)

Channelised (gullied section of Benty Hill)

Diverted (mid deposit track of Nein Head 3)

Scar stranded (mid-lower scar of Langdon Head)

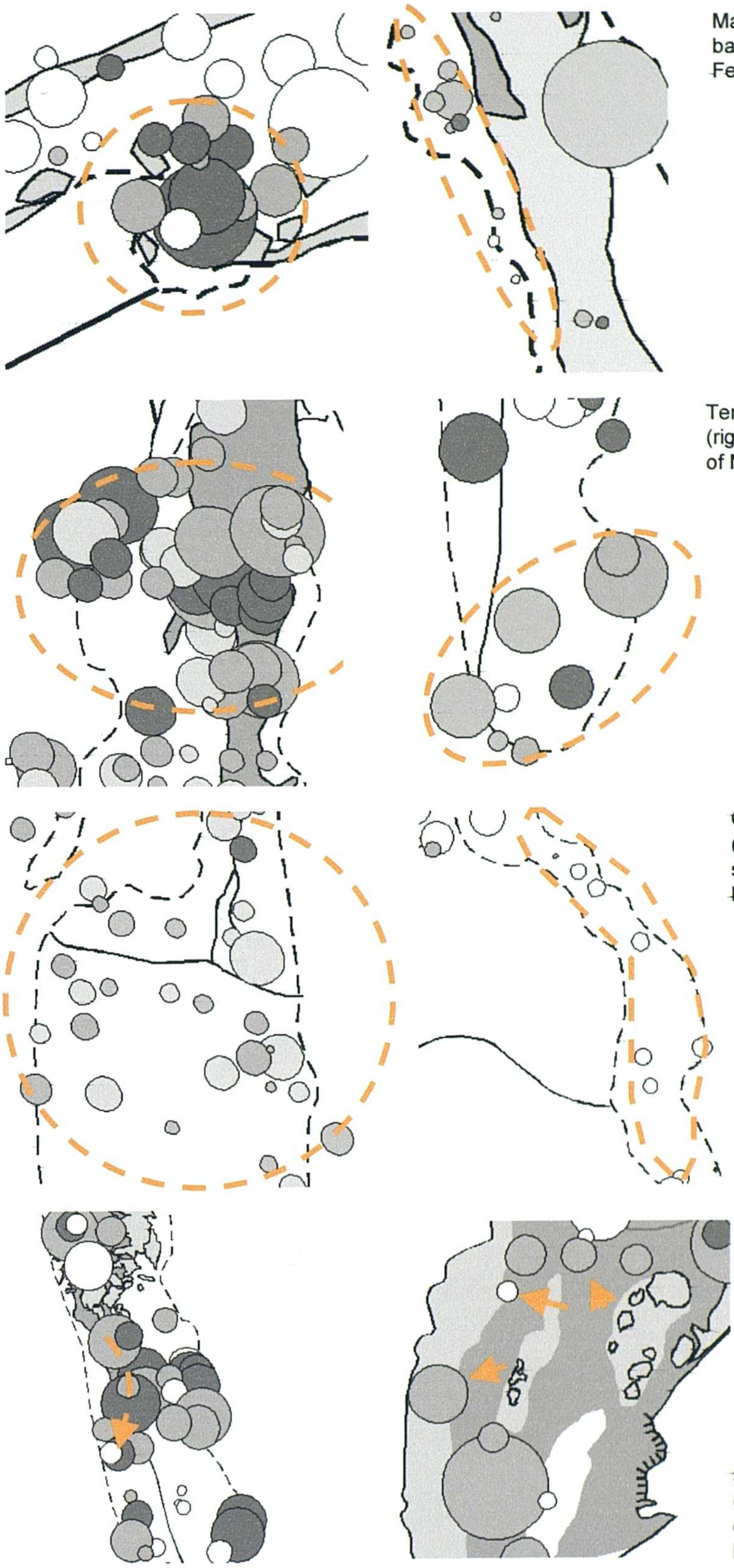


Figure 5.5. Matrix of example block patterns at North Pennine peat slide sites. Key to background shading may be found on Figures 4.6 to 4.8. Dashed lines and arrows delimit morphological units.

to slope position (close-up schematic views of block pattern are shown in Figure 5.5):

i) preferential down-slope alignment in channelised locations or in topographically confined locations, e.g. Feldon Burn central channelised section; Nein Head 2 channelised blocks in incised gully beneath major break of slope;

ii) preferential down-slope alignment in diverted block streams: Coldcleugh Head blocks diverted around primary lobe;

iii) preferential alignment normal to slope at the terminus of deposit lobes: Coldcleugh Head primary lobe; West Grain right bank side terminus; Benty Hill right bank raft breakaway lobe; pre-break blockfield in lower scar of Nein Head 2;

iv) random orientation in free flowing locations on planar slope sections: West Grain central blockfield within scar; Nein Head 3 in low density blockfields between jams;

v) alternating outward and inward oblique orientations where super-elevated: Feldon Burn adjacent to channelised section; Middlehope right bank side scar margin; Nein Head 2 right bank side leading deposit edge in upper scar;

vi) preferential alignment parallel and proximal to scar margins and at raft breakaways: Feldon Burn right and left bank scars; Langdon Head right bank side rafts;

vii) normal and oblique orientations in block jams: Nein Head 3 upper left bank side track; Coldcleugh Head behind primary lobe;

viii) preferential alignment along deposit margins: Nein Head 3 right bank side track.

5.2.3 Mapping of block dip

Figures 5.6a to d illustrate block dip maps at Nein Heads 2 and 3, Middlehope and Coldcleugh Head. As with block orientations, dip is highly variable both within and between sites. At the highest density locations (such as in the lower scar of Nein Head 2), block dip is at its most extreme, and frequently chaotic, with dip oblique to the down-slope axis. In

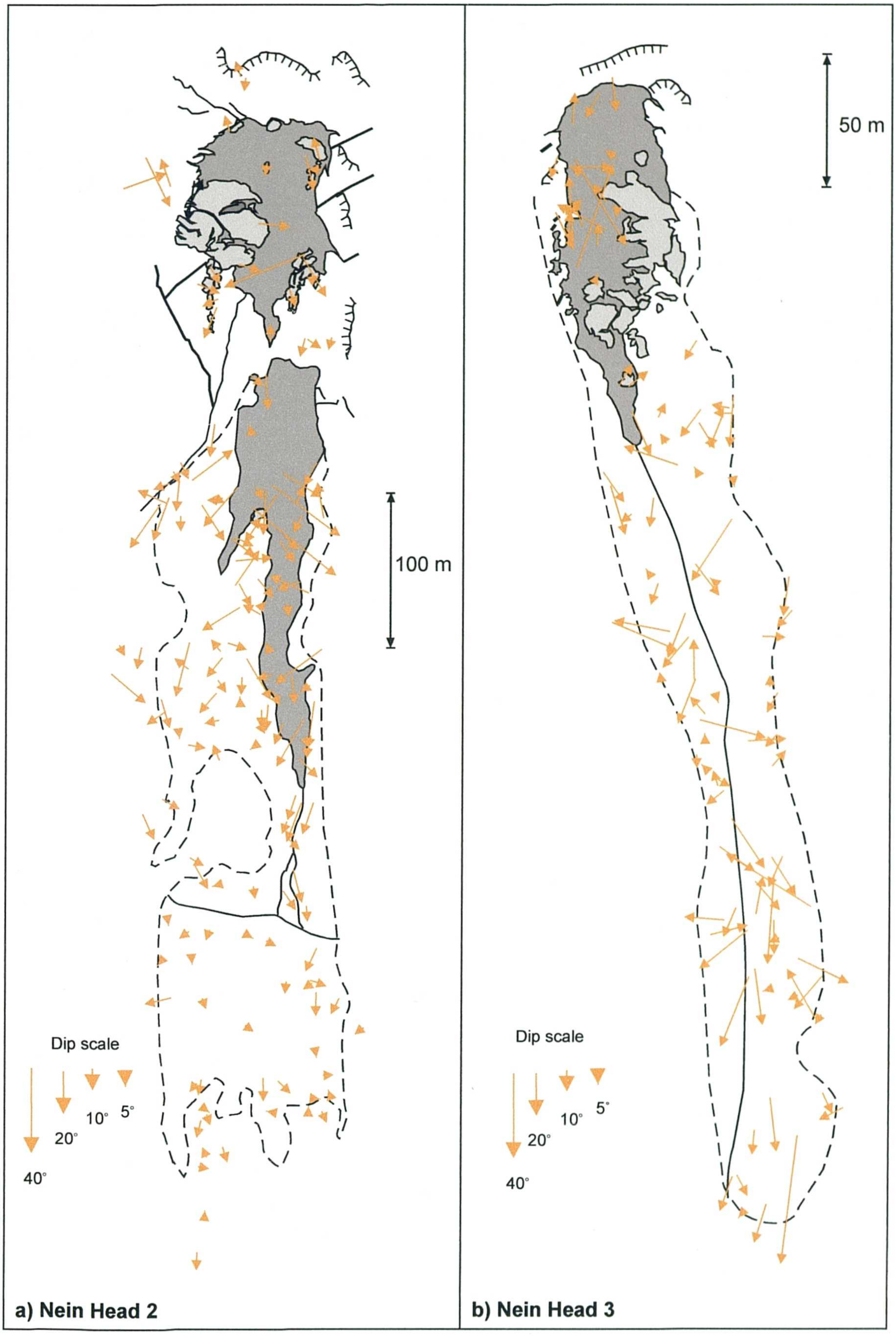
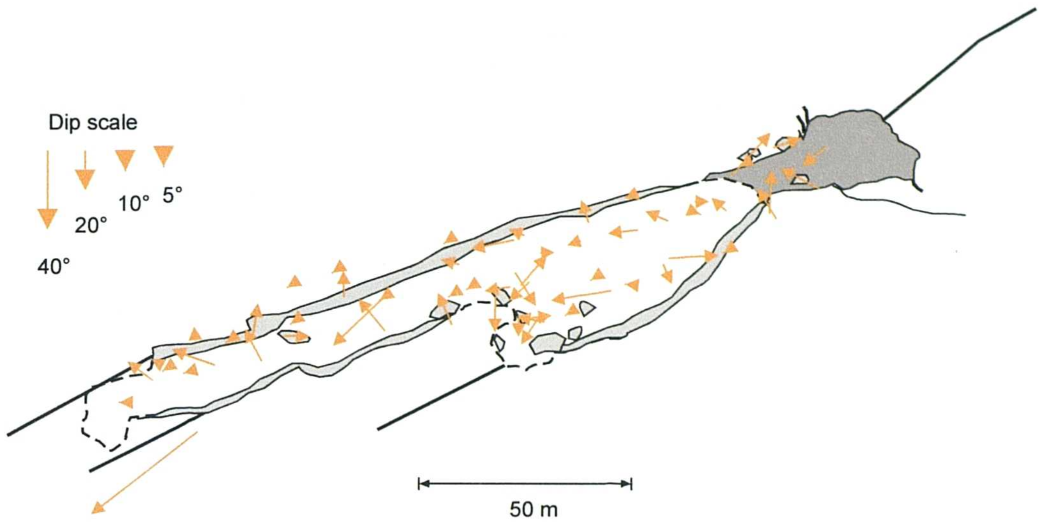
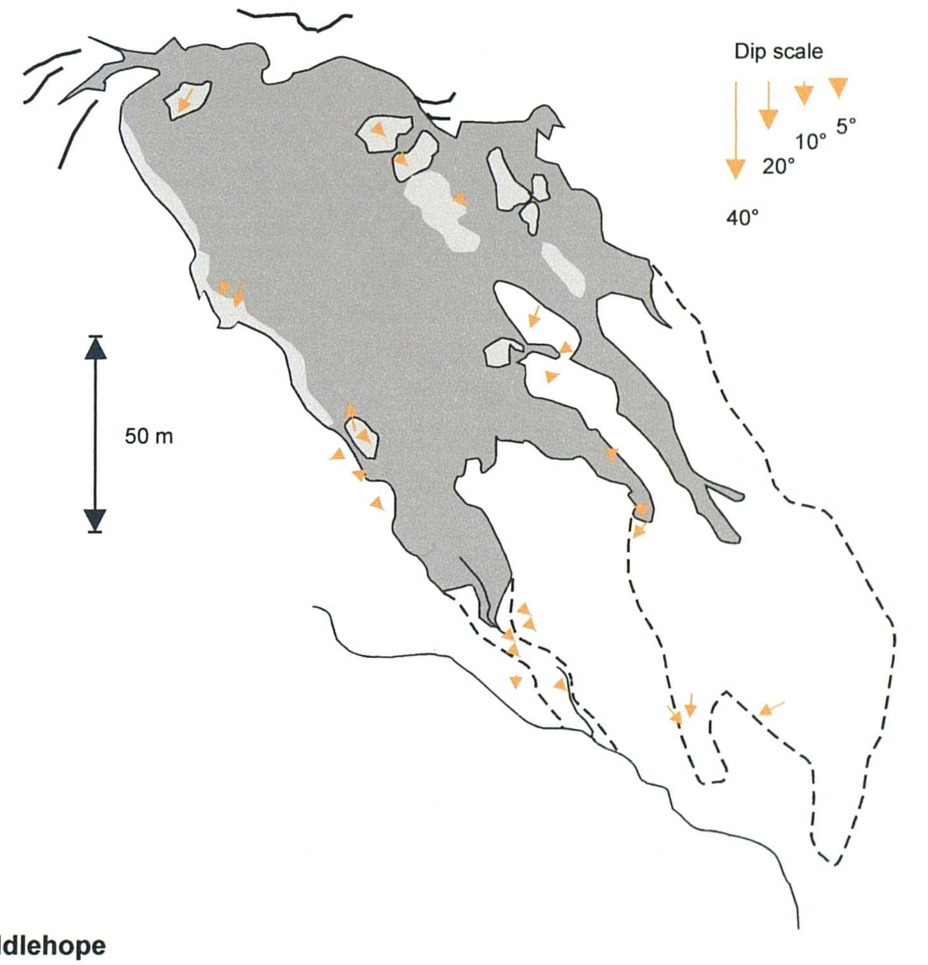


Figure 5.6. Block dip maps.

Continued...

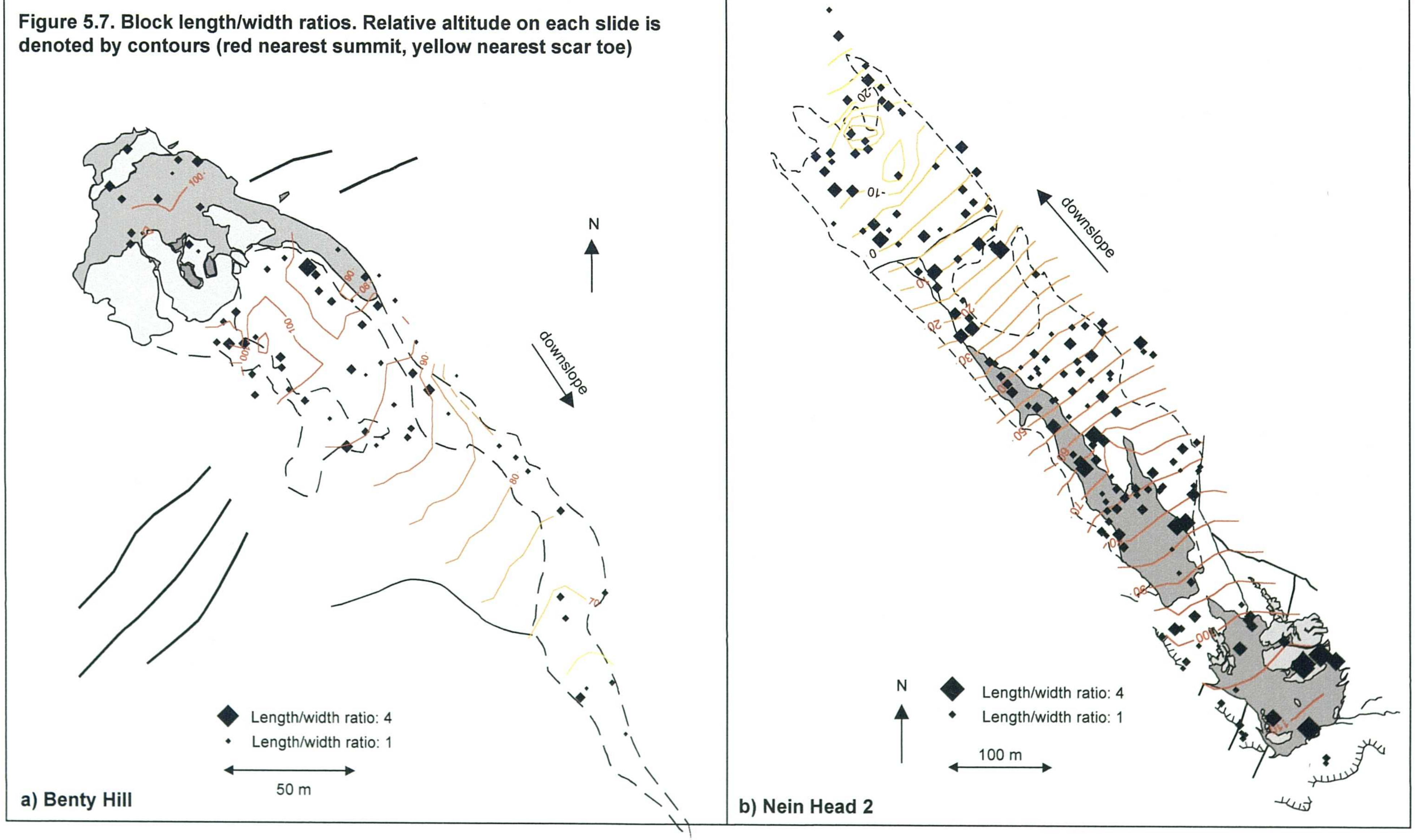
c) Coldcleugh Head





d) Middlehope

Figure 5.7. Block length/width ratios. Relative altitude on each slide is denoted by contours (red nearest summit, yellow nearest scar toe)



the lower density locations, such as at the foot of Nein Head 2, dip is much less extreme. Low density areas also show random dip direction, although backtilt (arrows pointing upslope) is generally rare, except in the vicinity of head scar margins. These patterns may relate to the degree of block interaction, which is a function of block density and/or cover. Where blocks come into frequent contact, they are likely to be arranged as a function of block-to-block contacts. The greater the block density, the more block-to-block contact, and the less ordered block dip.

At Coldcleugh Head and Middlehope, preferred dip is towards the right bank of each failure. Whether this relates to processes during failure is difficult to ascertain, particularly given the low sample number at the latter. At Coldcleugh Head, right bank side dip is most prominent along the right bank blockline and levee.

5.2.4 Mapping of block length/width ratios

Block length/width ratios were superimposed on the contour maps used to identify breaks of slope for the previously described maps. At Benty Hill (Figure 5.7a), two adjacent block lobes break away from the raft edges and have similar length/width ratios but different degrees of orientation. This suggests that block shape alone is not the only distinguishing factor in determining pattern and indicates that some other controls are also responsible for their arrangement. Equally, it can be seen that the smaller sub-rounded blocks that have entered the gully have very low length/width ratios, while the largest ratios are reserved for blocks that have only just broken away from the raft front edge.

Similarly, high length/width ratios are in evidence around the margins of the Feldon Burn scars but not in their centres. Elongate blocks dominate the scar margins of Nein Head 2 and Nein Head 3, but not near the rafted sections of Langdon Head.

An interesting pattern emerges at Nein Head 2, where length/width ratios appear to alternate down-slope (Figure 5.7b), initiating with high values in the upper scar and alternating over much of the first two thirds of travel distance. Shape becomes more variable thereafter, with more elongate blocks clustering along the deposit margins. In both cases, block size does not seem to determine shape, with the smaller blocks in the lower part of the track having a similar range of length/width ratios to the larger blocks in the upper scar.

5.2.5 Summary of block mapping

Qualitative interpretation of the peat block maps suggests that peat block forms and distribution patterns show considerable variability. At some sites (Nein Head 2, Benty Hill), there appears to be a clear decline in block sizes down-slope, while at others, block sizes vary continually down-slope, with some of the largest blocks surviving to the lower limits of the deposit tracks (such as at Nein Head 3). This may, in part, reflect variability in block origins across the scar areas. Both block orientation and block dip are difficult to interpret. Many sites show preferential alignment that can be clearly related to local topography. However, topography does not always dictate block orientation. Block dip appears to be more extreme and variable in the denser parts of blockfields, and in a down-slope direction. Back tilt of blocks occurs predominantly near scar margins. The degree of rounding shows little consistent variation with distance down-slope, although angular blocks at the sites showing size-sorting are usually concentrated in the upper slopes. The diversity in morphology at each site prevents the definition of general controls on block characteristics. However, collectively, the block data is informative in indicating general trends across the failure sites as a whole, as well as revealing aspects of detachment behaviour, and of local interaction with topography (such as gullies). The similarity in block numbers, form and distribution suggest that there is consistency in process activity across the slide population. Further assessment follows a zone-based analysis of block patterns.

5.2.6 Zonal analysis of block characteristics, by distance

Block dimensions have been related to slope distance. Therefore, it is hypothesised that block volumes will alter due to the cumulative effect of abrasion and downslope transport processes. Blocks furthest from their point of origin are likely to be the most affected. Orientation and dip are not considered here, as they are more likely a product of local transport, block interaction, and arrest factors.

Figure 5.8 shows variations in mean block volume, area and depth for the eight block-mapped failures. All sites show a general decline in block size with increasing distance downslope. Block depth remains relatively consistent, suggesting that block diminution is primarily a function of break up in the horizontal plane. Failures with short runout, or which are immediately coupled (e.g. Coldcleugh Head, Middlehope, Langdon Head) exhibit this pattern less clearly, probably because significant transport distances are required to

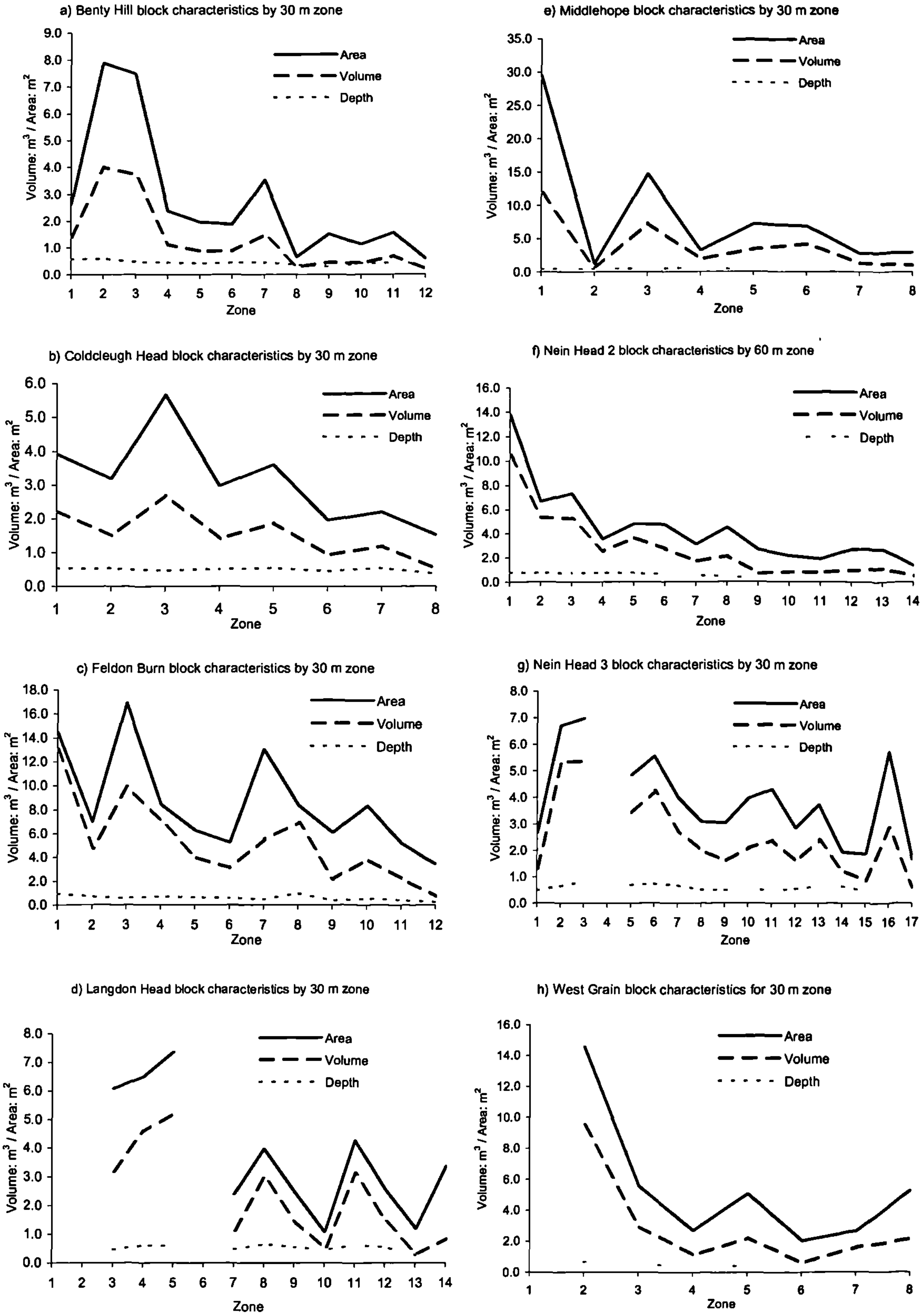


Figure 5.8. Variations in block dimensions with distance downslope for all sites.

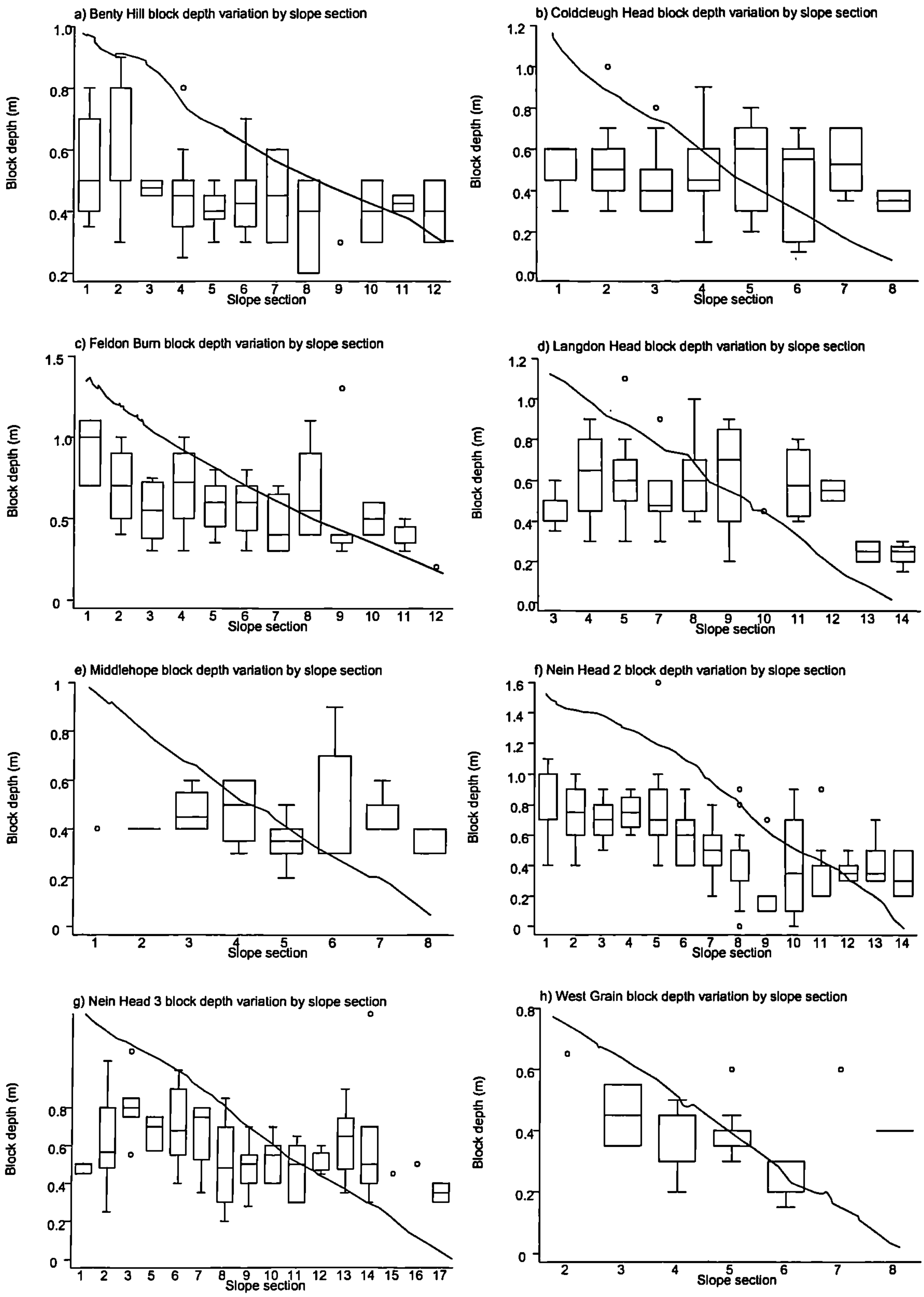


Figure 5.9. Block depth changes downslope for all sites with slope form also shown. Pronounced steps in block depth visible at Benty Hill, Feldon Burn and Nein Head 2.

produce a noticeably consistent decline in block size.

Variations in block depth are shown in Figure 5.9 in conjunction with slope form. Nein Head 2 shows a steep decline in block depth from zone 5 to zone 8, with depth remaining consistent from zone 8 down-slope. Benty Hill exhibits a similar rapid decline in block depth after a steep bench in zone 3. Gentle declines in block depth at West Grain, Feldon Burn and Nein Head 3 are clearly visible. Coldcleugh Head, Middlehope and Langdon Head show little consistent decline in block depth down-slope. Attempts to relate block depth to scar depth in the zones within each slide scar showed poor or null relationships.

5.2.7 Zonal analysis of block characteristics, by slope angle

While blocks may exhibit characteristics relating to the cumulative effects of transport distance, the range of slope forms to which the blocks are subjected is variable according to slope angle. These slope forms may, over short distances, exert local control over block characteristics. For example, blocks travelling over and deposited on gentle gradients may exhibit only slight dip. Blocks travelling over steeper gradients may travel faster and orient in such a way that they experience least resistance during transport, i.e. parallel to flow direction. Alternatively, blocks may roll over steep gradients and orient with their axes transverse to the direction of transport. In some cases, blocks may be reoriented in situ through impacts from other blocks, or be reshaped by subsequent weathering and erosion.

This section examines the local effects of slope angle on the strength of orientation and degree of dip of blocks over the slope lengths defined for each zone. For each slide, local zone slope angles were determined according to the transects displayed in Chapter 4. Slope angles were grouped into bin widths of 2°, starting at 0°, giving eight classes in total. Data was then treated according to block dip, and block orientation, as follows.

For block orientation, the dominant direction of transport was calculated for the blocks within each deposit zone (Figure 5.1b). This was determined by using the orientation of the downslope axis of the deposit within that zone as a zero reference orientation. Hence, blocks with their long-axis oriented parallel to the dominant direction of transport would exhibit an orientation, referenced to zero, of 0°. A block oriented transverse to the dominant direction of transport would exhibit an orientation referenced to zero of ±90°. A positive orientation would indicate alignment to the right of the zero, and a negative orientation alignment to the left. The effect of slope angle is considered in isolation from the inherited effects of slope distance by grouping all blocks by slope angle range. Hence all blocks across sites occurring on steeper slopes of between 14° and 15.9° would be lumped together. This tests the idea that slope angle is a dominant control on orientation.

Table 5.4 shows summary statistics for the full set of slope ranges upon which blocks were recorded. At no point were negative (or backtilted) slope zones encountered, and no blocks were found on topography that averaged over 16° for more than thirty metres in length. A majority of blocks (70%) were found on slopes between 4° and 10°. Given the range of slope angles over which the full slide features occur, this represents a concentration of the block population over the shallower relief. The average deviations of the block long axes from the dominant transport directions seem relatively low, between 1.4° and 30°. However, the large standard deviations imply that these average values are a product of a relatively high range about the mean value. Variability is widespread between the two transverse orientation limits of +90° and -90°. In most cases, there is a tendency towards positive deviation, or orientation away to the right of the dominant transport direction. There appears to be no physical basis for this, as the scars occur over planar slope sections, with no evidence of left-to-right downslope gradients. Mills (1983) noted a similar, unexplained phenomena in clast orientation in soliflucted hillslope material. Neither the data handling in this method, nor that of Mills (1983) should favour the generation of right-biased orientations.

Vector strengths, as a measure of the strength of the mean orientation, show a decline as slope angle increases through the slope range classes (Figure 5.10a), suggesting that blocks become more randomly orientated over steeper slopes. This decline may relate to increased process vigour over steeper slopes and correspondingly greater block interaction. When each site is considered separately, the block deviations described in section 5.2.2. are clearly shown (Figure 5.10b). The noted preferential orientation to the right side of the scars at Middlehope and Coldcleugh Head is visible, while the widespread variability within the large block populations at Nein Head 2 and Nein Head 3 is also visible.

Block dip, when considered within the set of slope ranges described previously, is highly variable in magnitude at all sites (Figure 5.11). The range of block dip is low in most slope

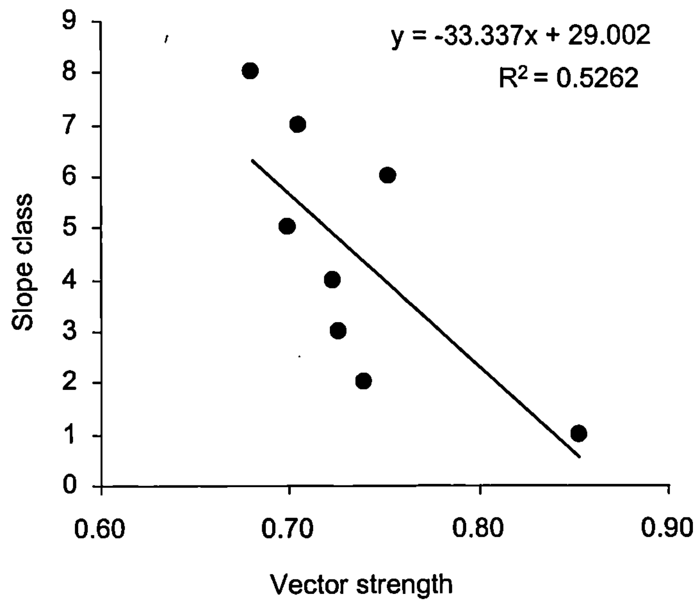
Table 5.4. Summary statistics for block orientation grouped by slope angle within deposit zones.

Slope range	Number of blocks per class	Mean deviation from dominant transport direction	Standard deviation	Minimum value	Maximum value	Vector strength
0.0 - 1.9	4	-30.3	36.6	-71	17	0.85
2.0 - 3.9	42	-3.1	44.3	-85	87	0.74
4.0 - 5.9	136	1.4	45.0	-89	88	0.73
6.0 - 7.9	133	9.6	45.2	-82	90	0.72
8.0 - 9.9	140	7.7	47.5	-90	90	0.70
10.0 - 11.9	65	-1.8	42.6	-89	67	0.75
12.0 - 13.9	41	12.0	47.6	-86	90	0.71
14.0 - 15.9	19	6.5	50.2	-89	78	0.68

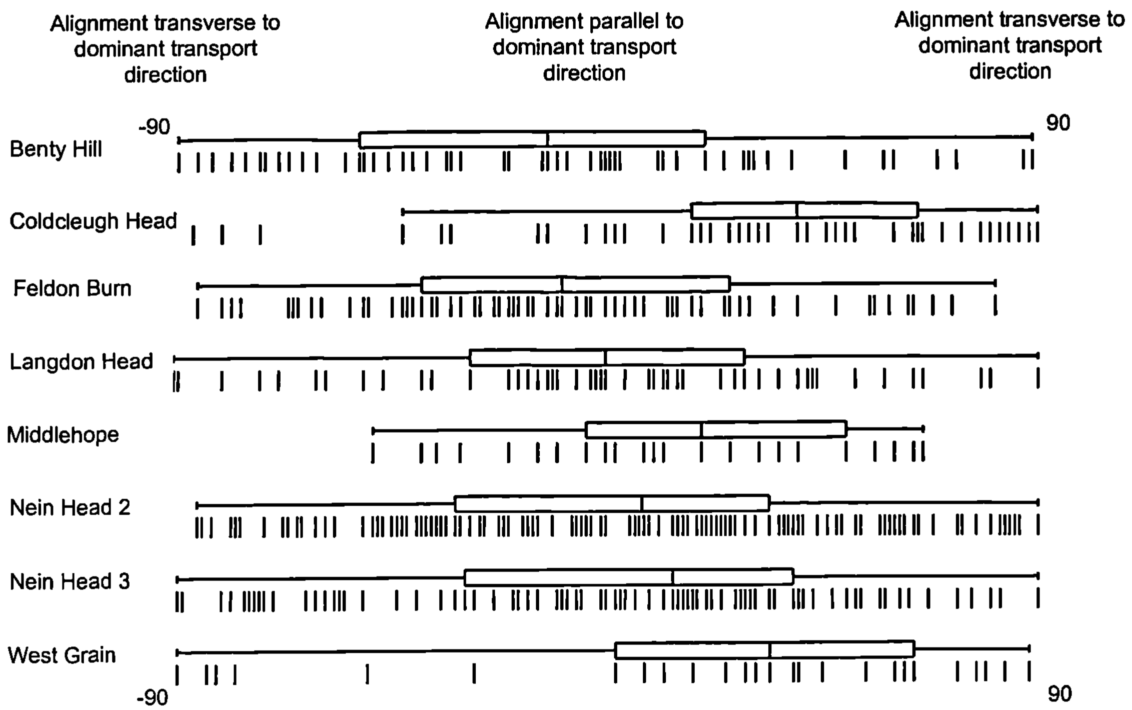
Table 5.5. Summary statistics for block orientation grouped by morphological zone

Variable	Observations	Mean deviation from dominant transport direction	Standard Deviation	Minimum	Maximum	Vector strength
terminal lobe	10	16.20	45.73	-60	85	0.74
non-terminal block jam	36	-19.78	43.85	-90	90	0.75
terminal block jam	17	28.06	59.42	-89	90	0.60
channelised	33	-8.27	43.34	-87	79	0.75
diverted	14	-3.21	24.40	-50	42	0.92
free-flow	159	7.92	44.47	-89	90	0.73
marginal	85	-0.62	45.14	-89	86	0.73
scar isolated	18	-11.17	50.41	-72	87	0.69

Figure 5.10a) Decline in vector strength with increasing slope angle (slope class) for all sites.



b) block orientations at all slide sites as deviations from dominant transport direction



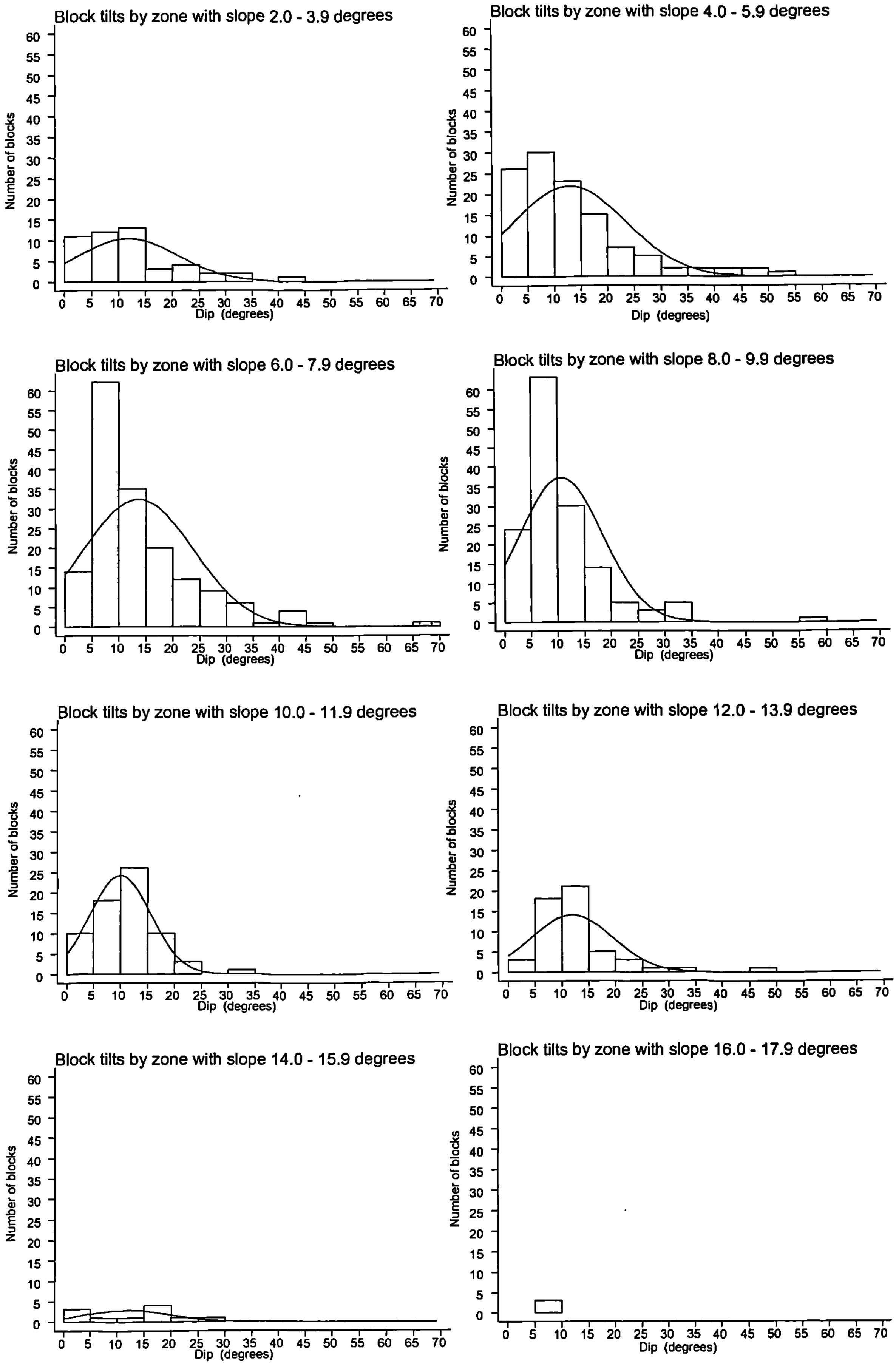


Figure 5.11. Block dip magnitude sorted by slope range for all sites. Bottom two graphs have insufficient sample size to be regarded as representative of block trends.

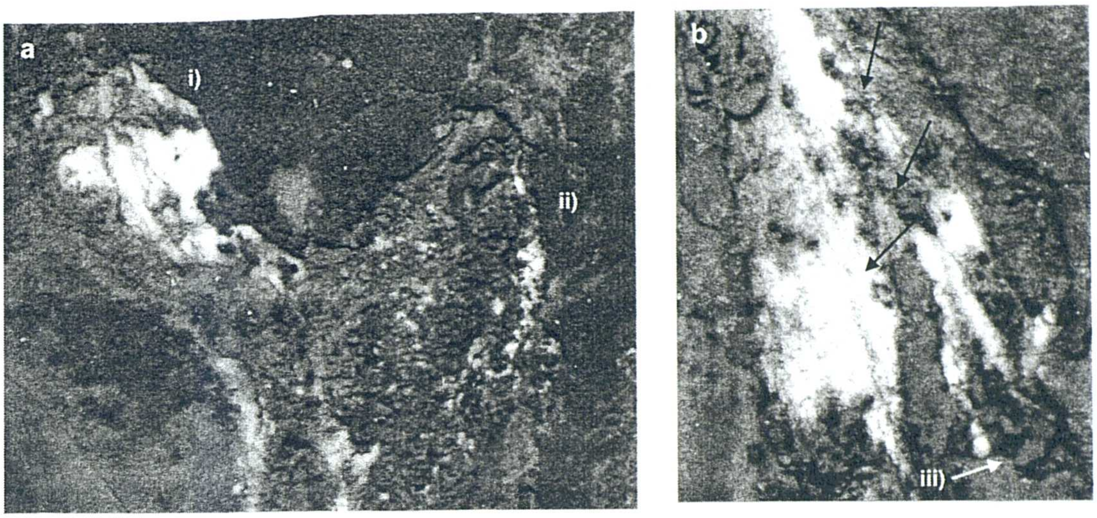


Figure 5.12. Choked and sparsely populated scar areas. a) Feldon Burn, substrate exposed and drainage visible (i), in right hand side scar, substrate largely concealed with extensive blocky deposit (ii); b) Langdon Head central scar area, isolated blocks in scar (arrowed), and larger raft broken away from local scar margin (iii).

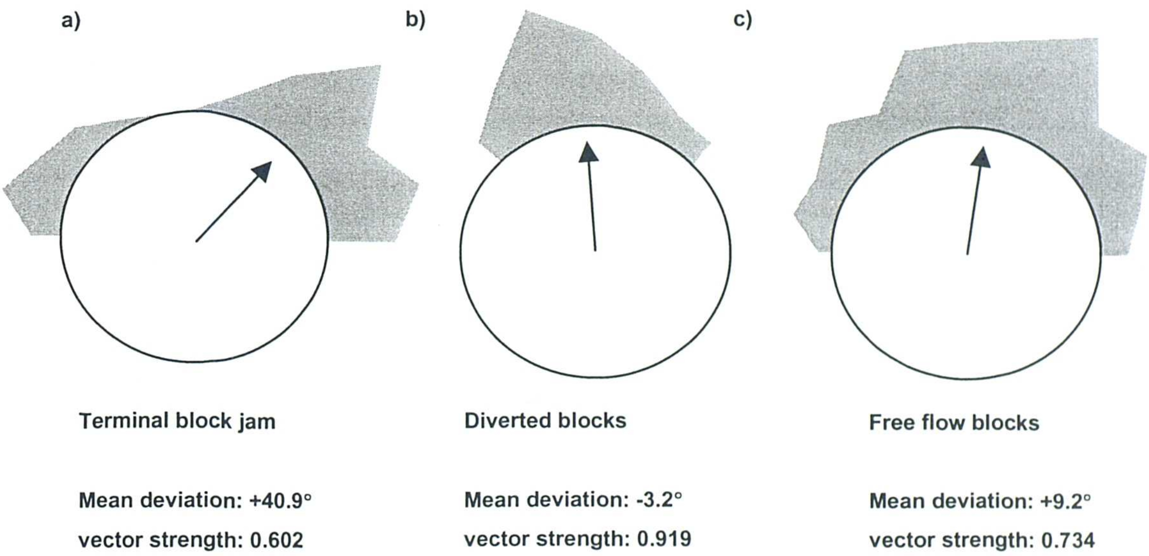


Figure 5.13. Three examples of Schmidt nets for a) bimodal block orientations in terminal block jams; b) unimodal and preferentially orientated blocks in diverted part of deposit; c) largely random orientation of blocks in free-flowing deposit zones.

zones (0°-15°) with a long tail of blocks with steeper inclinations. Block dips peak at between 55° and 60°. The consistency in dip ranges across all slopes suggest that something other than relief may determine dip, such as block density. Higher block densities and/or higher block covers would indicate greater likelihood of block interaction for any unit area considered (Figure 5.12). However, attempts to relate block dip to block numbers per zone, and block dip to block area per zone produced no significant relationships.

5.2.8 Zonal analysis of block characteristics, by morphological context

Block deviations were plotted as Schmidt nets, according to the morphological zones described earlier. Figure 5.13a, b and c, and Table 5.5 illustrate the Schmidt nets for three differing distributions, and summary statistics respectively. Figure 5.5 shows schematic examples of each morphological zone, enlarged from the slides in question. In morphological zones associated with pronounced grouping of blocks (such as lobes and jams), deviation is most pronounced (e.g. 28° in terminal block jams). In some cases it is bimodal (terminal block jam) suggesting a tendency towards orientation transverse to flow direction. In linear morphological zones associated with restricted lateral movement (e.g. channelised or diverted blocks), deviations are much less. Schmidt nets indicate unimodal distributions with high vector strengths (e.g. 'diverted' vector strength = 0.92). Outside of these morphological units, alignment is generally oblique to dominant transport direction and without pattern.

5.2.9 Summary of zonal analysis

Zone mean block dimensions decline down-slope at most sites. The maintenance of block length/width ratios (see Chapter 4, section 4.2.5.2) at the expense of volume (section 5.2.6) indicates that block diminution occurs through wasting of all axes of the blocks. Volume changes more rapidly with area loss than with abrasion-loss of block depth. Although block depths are limited at their upper extent by local scar depth, depth does not consistently relate to source depths once transported.

The effect of slope on block orientation and dip is inconsistent. Mean deviations of block a-axes to the dominant down-slope flow direction suggest common alignment when blocks move as block streams around obstacles, or through constrictions. Bimodality and high variability result when blocks move entirely independently of other solid masses, or where densities are sufficiently high that block-block collisions produce random alignments. Related to this idea is the distribution of block dip, which does not significantly relate to local slope, and is more a function of density or area coverage in the most densely blocky slide scars.

Sorting of block attributes by morphological zone reveals slight tendencies towards transverse block orientations and high block dips in areas of compression and clustering, and preference towards flow parallel orientation in zones of extension and lateral constriction. The overriding tendency of most blocks is to form oblique orientations to the flow through much of the runout zone, regardless of slope, distance travelled or morphological context.

5.3 Event sediment budgets

Event sediment budgets for the eight block-mapped sites are shown in Figure 5.14. Summary budgets for these, and other peat slide sites are shown in Table 5.6. All curves are cumulative, with the zones representing 30 m slope lengths, except in the case of Nein Head 2, where zones consist of 60 m slope lengths. Volume displaced (or peat mobilised), volume deposited, and the nature of the deposited peat are shown in each case. The difference between volume displaced and volume deposited at the termination of the slide (i.e. last zone) represents the volume delivered to local stream systems, and/or the volume unaccounted for (lost) due to post-failure site modification by weathering. This can be easily determined where there is direct coupling of scar and channel (e.g. Langdon Head, Middlehope), as it is assumed that all unpreserved deposit entered the channels during the event. Volumes are shown in the figures and tables, assuming a wet bulk density of approximately 1000 kg m^{-3}. Assuming this density, values for volumetric losses can be considered equivalent to tonnage losses.

In terms of magnitude, the failures mobilising the largest volumes are Nein Head 2 (22 925 m^3), Hart Hope (18 655 m^3) and Langdon Head (18 570 m^3), and the smallest by a significant margin is Coldcleugh Head (420 m^3). Most failures have displaced in excess of a few thousand tonnes of peat.

Slide name	Total displaced volume (m^3)	Total block volume (m^3)	Total raft volume (m^3)	Total slurry volume (m^3)	Delivered volume (m^3)	Sediment delivery ratio
Benty Hill	4880	230	3460	725	470	0.10
Coldcleugh Head	420	200	0	235	0	0.00
Dow Crag	14425	0	1825	1360	11240	0.78
Feldon Burn	8875	3845	1100	1185	2745	0.31
Hart Hope	18655	1544	1720	1427	2029	0.30
Iron Band	7690	127	765	460	6345	0.83
Langdon Head	18750	850	8090	490	9140	0.49
Meldon Hill East	1825	0	140	435	1250	0.68
Meldon Hill West	3940	0	30	530	3380	0.86
Middlehope	3645	180	155	620	2690	0.74
Nein Head 2	22925	1260	5170	3375	8130	0.35
Nein Head 3	6200	980	2015	3200	0	0.00
West Grain	4605	110	3170	870	0	0.00

Table 5.6. Summary figures for sediment budget information at all sites

In the case of long, continuous scars that maintain their length/width/depth profiles over relatively long distances (Langdon Head, Feldon Burn), sediment flux is relatively constant down-slope, although the flux is modified by the addition of further sediment throughout much of the slope length. Where scars are short relative to the runout zone, displacement is rapid and cumulative displacement curves steep. Sediment transport and deposition rapidly becomes dependent upon scar-external controls such as morphometry.

Table 5.6 illustrates that of the eight sites considered here, only Coldcleugh Head, Nein Head 3 and West Grain are completely uncoupled, with runout zones failing to encounter any local drainage networks. The delivered volume in part considers sediment loss, or the sediment volume that cannot be directly accounted for. This leads to artificially high sediment delivery figures for sites at which raft and block numbers (i.e. preserved sedimentary evidence) are low. It seems reasonable given the extent of coupling at most sites, that most of this sediment was ultimately deposited within channels. However, some may have been reincorporated into the blanket surface as very fine aggregates of peaty debris. Assuming that a majority is delivered, of the coupled sites Middlehope, Feldon Burn and Langdon Head have the highest sediment delivery ratios (0.74, 0.60 and 0.49 respectively). Middlehope and Langdon Head abut directly onto the headward reaches of local valley channels (Figure 5.15a, b), while at Feldon Burn, the twin scars and hollowed out 'aisle' beneath them are situated in former converging stream heads (Figure 5.15c).

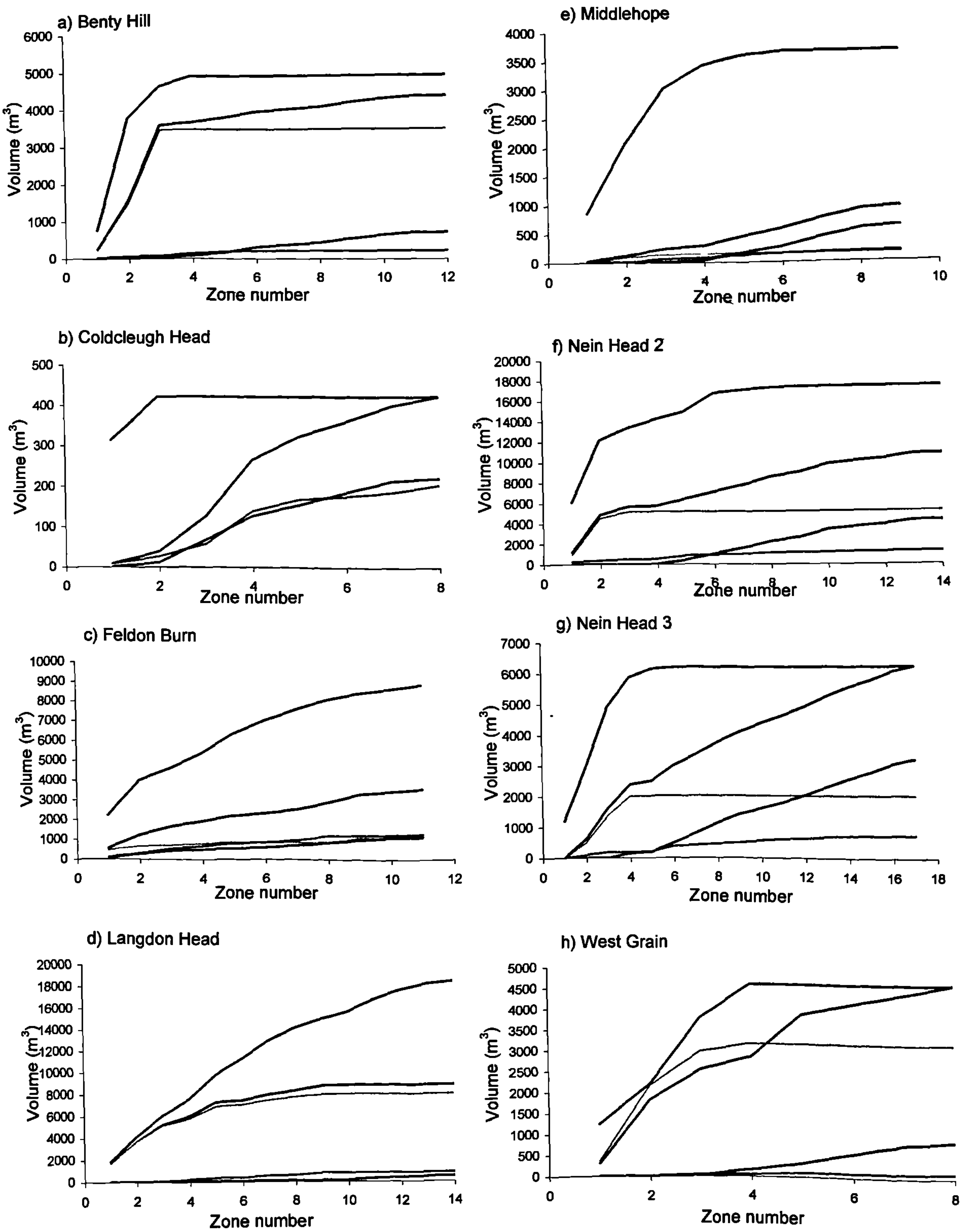


Figure 5.14. Event sediment budgets for block mapped sites

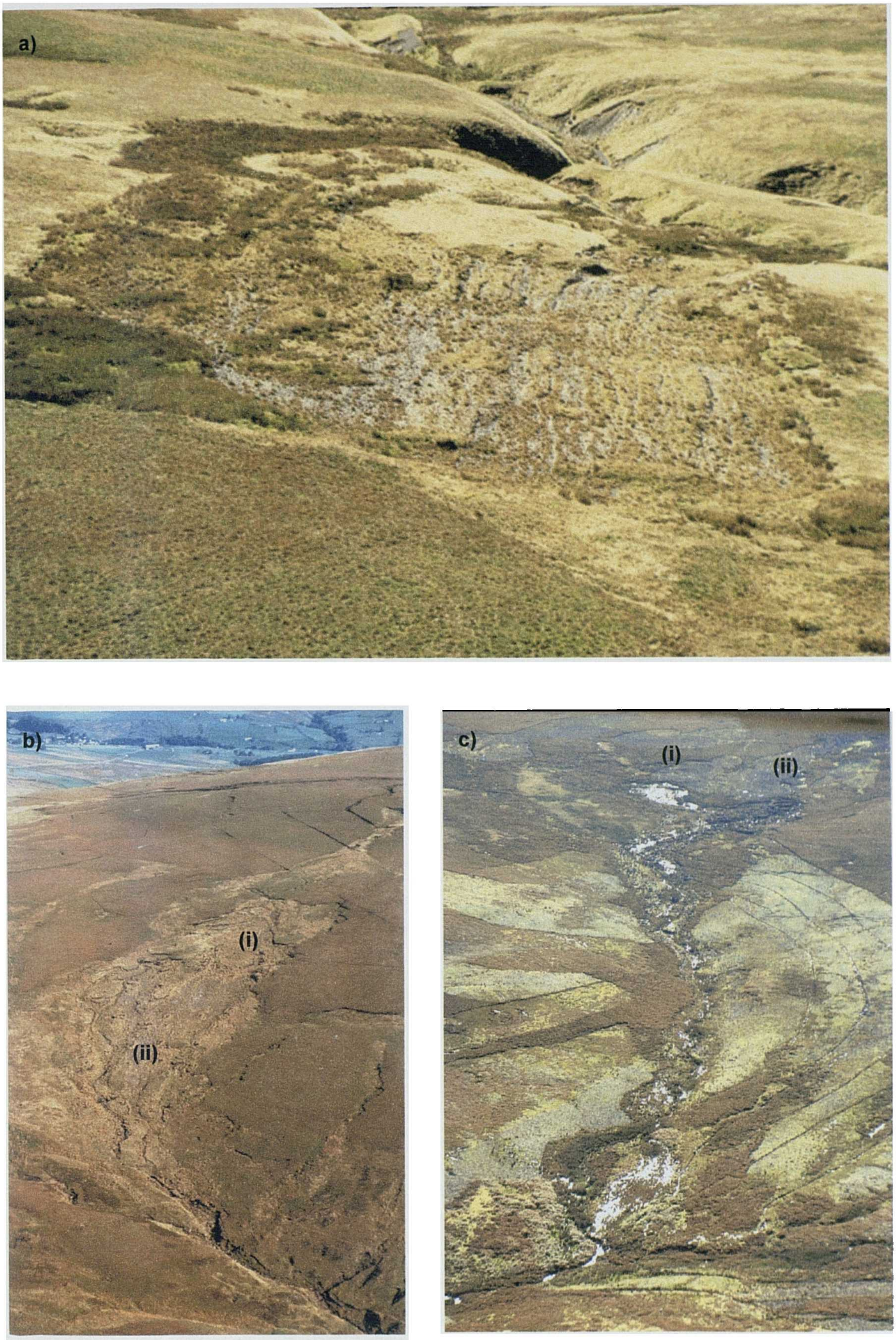


Figure 5.15. Slope channel-coupling at North Pennine peat slides. a) Middlehope, almost all displaced material discharged directly into gully head. (Note shallow slope failures visible on gully sidewalls, may indicate localised tendency for slope instability); b) Langdon Head, upper rafts stabilised (i), but lower scar (ii) largely excavated into Langdon Beck beneath. The scar probably occupied a former gully head; c) Feldon Burn, twin scars (i and ii) feed extensive channelised track.

Sediment delivery ratios are generally high across the whole data set, except where systems are decoupled and no sediment is delivered at all.

Raft, block and slurry contributions to the deposit volume vary between sites. Raft volumes make up a significant proportion of the displaced volumes at Benty Hill, Langdon Head and West Grain, where they comprise in excess of 40% of the total displaced volumes. Rafting is still significant at Nein Head 2, Nein Head 3 and Feldon Burn, where 22.5%, 32.5% and 12.5% respectively of the disturbed peat is deposited as rafts. The degree of disturbance and/or proximity of the scars to locally steep relief at the other failures is such that blocks represent the largest coherent peat masses remaining. Failures initiating over convex slopes (such as Benty Hill and Nein Heads 2 and 3) see most of their raft-deposited peat stabilise before reaching the convexities. Only at the rectilinear slopes of Feldon Burn, Langdon Head and West Grain does raft deposition continue for over 50% of the overall disturbance length.

Blocky deposits represent a relatively minor proportion of the total sediment volume at most sites (generally < 15%), except at Coldcleugh Head (approximately 50%). In almost all failures, blocks are deposited continuously from the headscar to the down-slope limit of the runout zone. Where rafting is extensive in the upper reaches of the failures, blocky deposition increases as volume deposited by rafting declines (e.g. Benty Hill, Nein Head 2, Langdon Head). This is significant in elucidating the ways in which the peat mass breaks down into successively smaller morphological units, and by implication, in the consideration of spatial distribution of process types (sliding, flowing). Raft breakdown leads to rapid block production immediately downslope. Then the greater surface area of block side-faces exposed to impacts results in slurry formation.

Figure 5.16 illustrates the rate of conversion of rafts into blocks with distance downslope. Block numbers per zone are calculated for each 30 m slope length at each slide. These calculations are based upon the values for total block volume per zone calculated in the site sediment budgets, and on regression equations derived from the site-specific declines in block volume shown on Figure 5.8. The rate of increase of block numbers is frequently associated with decrease in block volumes downslope. For example, at Benty Hill (Figure 5.16a), the rafted component of solid deposit is truncated after 90 m of transport distance (zone 3), and there is an associated increase in the rate of block generation. This suggests that local downslope increases in block numbers (in zones 4 and 5) may relate to the break up of larger rafted debris into many smaller solid components. This ramped block generation is also shown at Langdon Head (Figure 5.16d; zones 5 to 9), Nein Head 2 (Figure 5.16f, zones 3 to 4) and Nein Head 3 (Figure 5.16g; zones 2 to 6). This agrees with suggestions in the previous chapter that rafts are a morphological precursor to blocks, and that raft break-up produces many smaller blocks. Attempts to apply this approach to blocks and slurry would require a more thorough field understanding of the preferred spatial distribution of slurry volumes. However, Figure 5.17 combines information from the sediment budgets and block abrasive break-up calculations to illustrate for two sites the interdependency of the three morphological units of rafts, blocks and slurry. In both cases, raft forms dominate the deposit volumes in the first few tens of metres of transport. These are rapidly converted into numerous block forms, which peak in number at a distance downslope. This distance is probably determined by a peak in process activity responsible for larger mass break-up, and beyond which blocks degrade entirely into slurry. The increase in slurry at the expense of block numbers is shown clearly at Langdon Head in zones 10 and 11.

As Figures 5.17 and 5.14 show, slurry varies in importance between sites. At Coldcleugh Head, the only site without rafting, slurry is particularly significant (> 50%). The deposition of slurry and peat initiate at approximately the same slope position within failure sites, and while block deposition dominates initially, slurry becomes the dominant contribution to deposition in the lower slopes over either rafts or blocks (e.g. Nein Head 3, Middlehope, Coldcleugh Head).

The sites for which block mapping was not available (Dow Crag, Hart Hope, Iron Band, Langdon Beck, Meldon Hill East and West) are comparable in terms of sediment displaced (from 1825 m^3 at Meldon Hill East, to 14 424 m^3 at Dow Crag). However, sediment delivery is generally high (all sites have sediment delivery ratios over 0.68). Raft and block volumes are very low to absent at all sites, and the traceable terrestrial limits of the runout zone suggest only limited volumes of slurry (generally less than 20% by volume). Comparison with written accounts suggest a significant volume of deposited blocks at Dow Crag:

> '...there are still numerous huge lumps of peat on the surface of the clay, but most of it has disappeared and the banks of the scar are ten foot high at the northern end, where the gill itself begins...'
>
> (Hudleston, 1930, p290)

Photographs taken shortly after the event at both Iron Band and Meldon Hill (Figure 4.9 and 4.10) suggest that blocks were in evidence shortly after failure, but these could not be

Figure 5.16. Conversion of raft components into blocks with distance downslope. Each deposit zone is equivalent to 30 m in length.

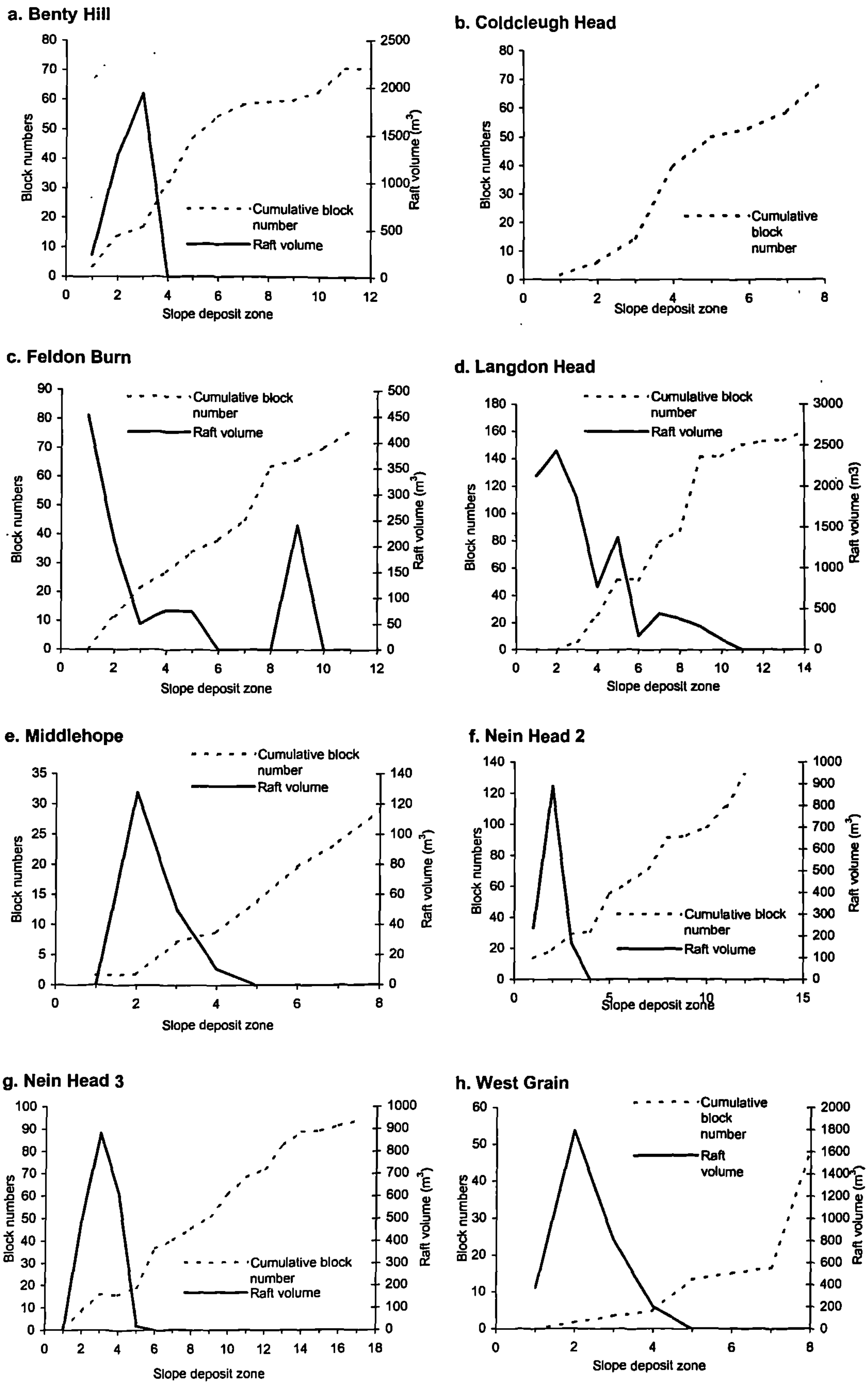
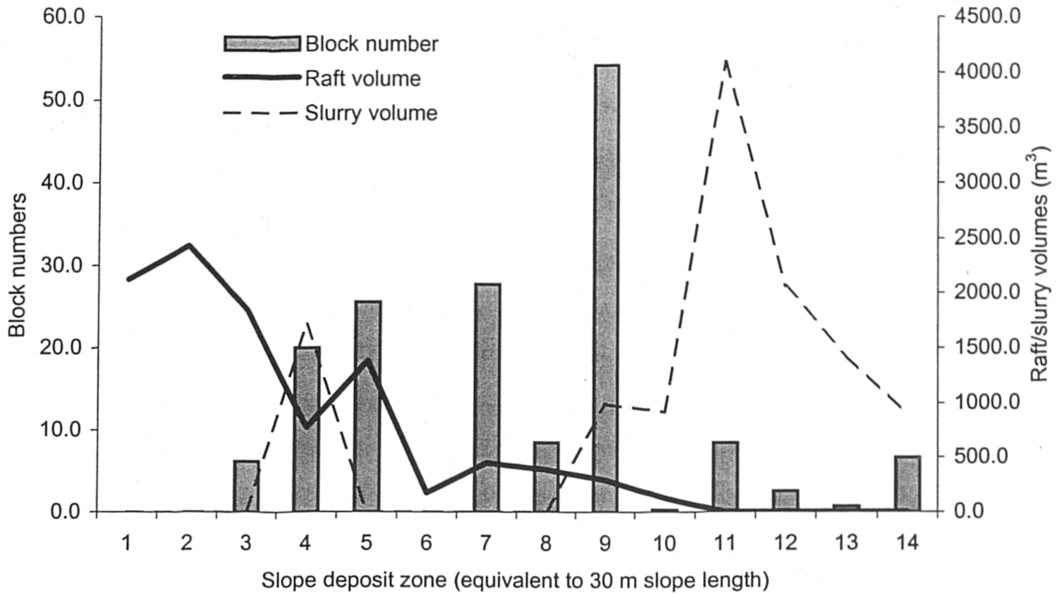
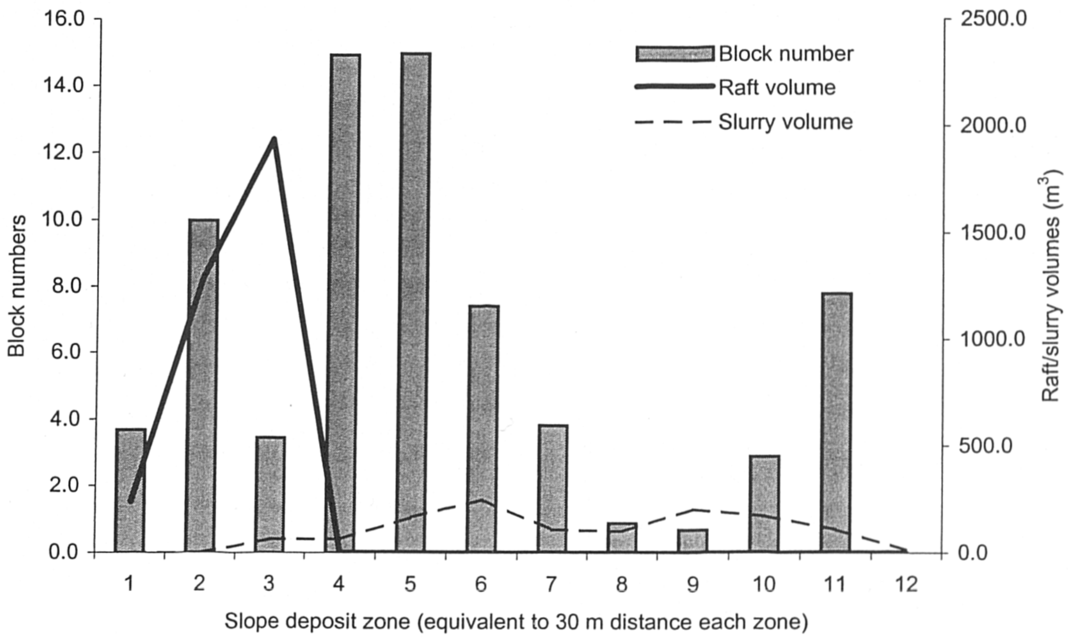


Figure 5.17. Spatial dependency in raft and slurry volumes, and block numbers

a. Langdon Head



b. Benty Hill



mapped without prior knowledge of their location in the present day.

5.4 Discussion

The introduction to this chapter specified four main objectives and associated hypotheses relating to the nature of transport and modification of debris. Each of these themes is now considered in turn.

5.4.1 The spatial distribution and relative significance of deposit types

The first hypothesis in section 5.0 suggested that the dimensions of solid deposit would decline with increasing distance downslope. Chapter 4 indicated that raft sizes generally decreased with increased transport distance. Section 5.2.1 used map interpretation of block size, shape and distribution to examine the spatial distribution of blocky deposit. The distribution of block dimensions (or clast grading) revealed considerable variability in block dimensions both down and across slope, and between sites. The largest blocks were associated with scar margin detachments and raft break-up, with blocks often breaking away in masses parallel to the raft leading edges. Raft break-away blocks were generally located above the steep parts of convex slopes at which the rafted sections had come to rest. As block transport was traced further down-slope, block size usually declined.

Zone based analysis of changes in block dimensions supported this interpretation, revealing a consistent but variable decline in block volume and block area down slope. Block depth, while decreasing slightly, was far less consistent. Depth appeared to exert little control on block size, suggesting that basal abrasion, while likely, was not the dominant process in block diminution. Variable block depths may suggest variable local abrasion rates. This corresponds with the reports of occasional blocks with clay-layers attached (e.g. Crisp *et al.*, 1964; Carling, 1986; Warburton *et al.*, in press), but a more general lack of clay-layers in the majority of the blockfield.

5.4.2 Controls on peat mass break-up in transport

The second hypothesis in section 5.0 suggested that the percentage of rafts and blocks would decrease downslope, and that the percentage of slurried deposit would increase.

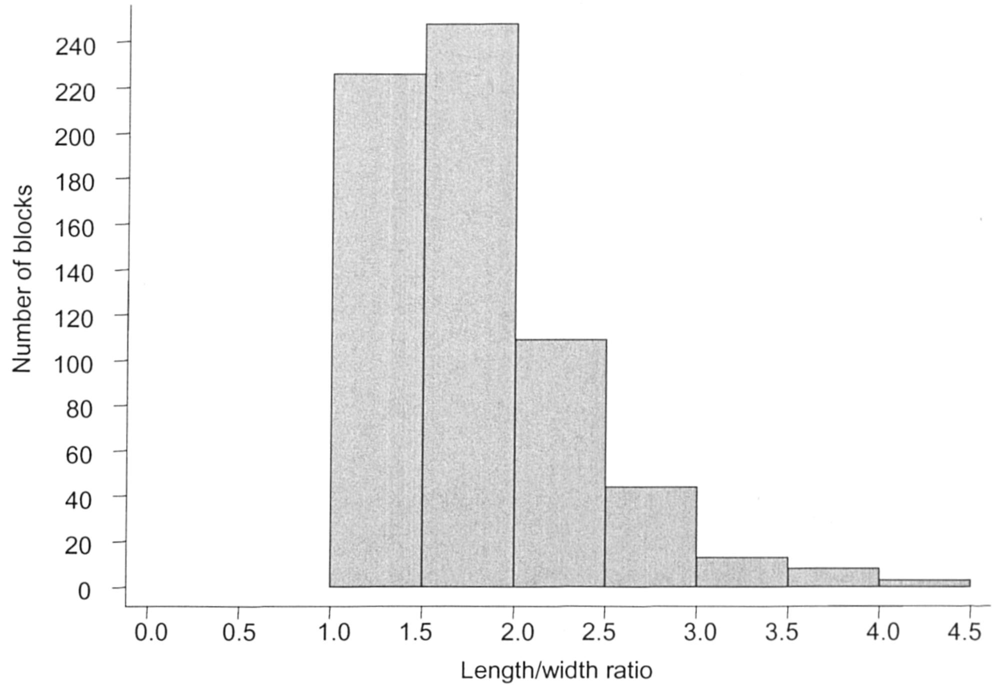
Chapter 4 illustrated the continuum of form between rafts and blocks, as the size of the largest solid deposits declined with increasing transport distance. This chapter has primarily been concerned with the break-up of blocks and the generation of slurry. A clast sedimentological approach was used to examine the controls upon block break-up with increasing travel distance. The reduction in block size associated with increased travel distance mirrors other geomorphological processes, most notably the transport of fluvial bedload in structurally weak clasts. One of the more notable studies of process control on particle shape is that of Sneed and Folk (1958), who examined fluvially transported clasts of differing material origin in Colorado. Peat blocks may be considered analogous to many sedimentary clasts, in being structurally weak along bedding planes, and hence relatively easy to degrade.

The breakdown of larger peat blocks to smaller ones, controlled by structure, is shown in the examination of length/width ratios. Figure 5.18 shows length/width ratio plots for all blocks from all sites. The summary plot (Figure 5.18a) indicates a peak of blocks approximately 1.5 times as long as they are wide. The length/width ratio at double this length (3.0) corresponds to the beginning of a long and narrow tail of longer blocks. The individual site plots suggest that this long tail is common to all sites, and that most sites follow the general pattern of Figure 5.18a. The low frequency range of block sizes in the tail may represent forms above the threshold strength for stable transport within the runout zones of peat slides. The tendency for elongate break-up of the peat mass is emphasized by the presence of such masses at bog burst sites. This is considered further in Chapter 8.

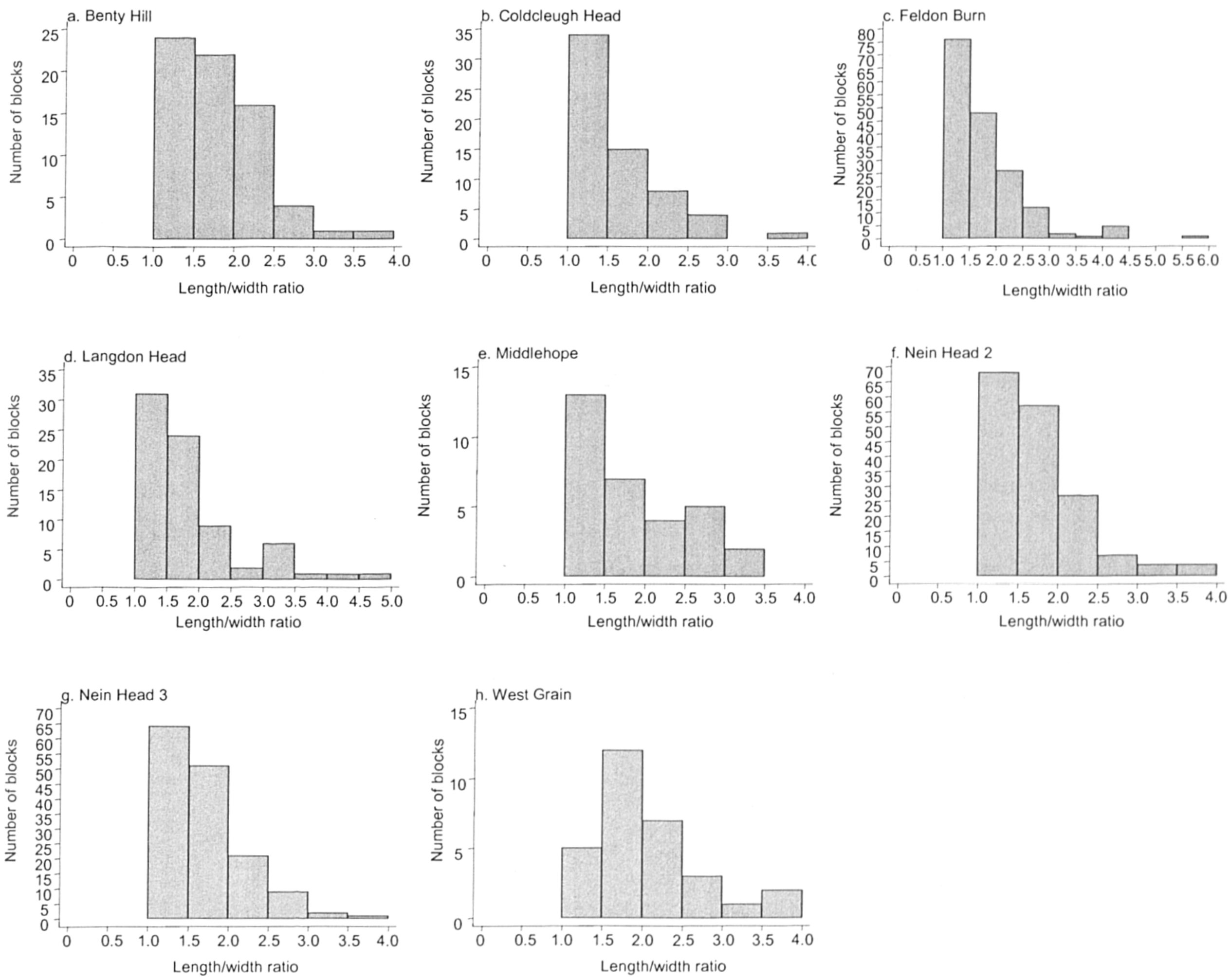
Block shape, as embodied in angularity and roundness revealed few consistent spatial trends at any of the sites. Sub-rounded and sub-angular blocks comprised the major body of the block population. Angular blocks were sparsely distributed, and more usually in the proximal failure zone, suggesting strong preservation of detachment form with limited transport. Rounded blocks were sparser still, and were found scattered throughout the distal zone of runout. The lack of rounded blocks may relate to a dominance in sliding in transport, which would be favoured by the length/width ratios in Figure 5.18. However, it is also possible that no rounded blocks are found because upon acquisition of equivalent a-, b- and c-axes, rolling initiates and blocks completely degrade into slurry. Hence, no evidence of rolling is found. Absence of evidence is not evidence of absence. For fluvially transported particles, Sneed and Folk (1958) suggested that smaller particles become more rounded, and larger particles less so with increasing travel distance. This corresponds reasonably to the situation in peat slide deposits, where smaller particles

Figure 5.18. Length/width ratios for blocks, i) for all sites, ii) a-h, individual sites

i) for all sites



ii)



become incorporated in the moving slurry, and larger masses stabilize (perhaps due to greater basal friction).

The variability of both shape and size across slope suggests continual, but localised and independent raft break-up, with larger rafts moving out in the initial stages of movement, and on breaking up, creating zones of higher local block density. As a result, density is variable within the slide area. Larger block sizes in the lower slopes may represent structurally coherent, or locally entrained coherent peat masses that have been more able to withstand destructive processes in transport. Such masses would either have particularly coherent surface vegetation, and be held together through tensile strength, or may have acted as lobe fronts, and undergone limited interaction with other blocks. Raft transport with block break up at the tail has been reported by Lewkowicz (1990) for active layer slides. Process type and activity is considered in the next section.

5.4.3 Process activity in the raft and block sediment fractions

The third hypothesis in section 5.0 suggested that patterns of sedimentation would indicate variations in the nature and extent of process activity. Peat block sedimentology, applied through a zonal approach to morphology, slope and transport was used to examine block patterns as a basis for process interpretation. Initial analysis of block orientation suggested some correspondence with local morphological units. A broad tendency for elongate blocks to orientate oblique to the predominant flow direction was noted at most sites. Zones of normal and parallel aligned blocks were noticeable by their presence, the former in high clustered morphological zones, and the latter where channelised. Morphologically dependent orientations were observed at all failures, and while testing by morphological unit did not reveal significant patterns in orientation, physical parallels in non-peat mass-flows do correspond to some of the patterns or fabrics observed.

In locally dense block fields, interpreted as zones of compression, and at the terminal points of deposit lobes, block orientation appeared to be predominantly transverse to the down-slope axis. In more sparsely populated zones, and constricted areas (such as channels and diversions around block jams), orientation appeared to be oblique-to-parallel. In free flowing areas, away from lateral margins and on planar slopes (either within the scar or over the undisturbed peat blanket) block orientation was predominantly oblique to the slope.

A considerable body of literature exists to support process inference from clast fabric, although some doubt has been placed on its emphasis by Bennett *et al.* (1999) and Dreimanis (1982). Clast orientation (rather than clast size and shape) has been used in the interpretation of fluvial, glacial, sub-aerial and mass movement processes. For fluvial processes, transverse (normal) orientation of long axes has been associated with protracted rolling (Major, 1998) and saltation of clasts (Todd, 1996), frequently accompanied by imbrication. In peat slides, the former is unlikely due to the structural weakness of the peat mass, and the lack of blocks with equi-dimensional b- and c-axes attests to this. Equally, saltation in a shallow slurry is not possible unless blocks become very small (b-axis < 0.12 m, i.e. mean slurry depth). Imbricated, or stacked blocks are rare to absent (as noted by Blair (1999) for rock avalanches), with blocks more usually adjacent to one another after recent separation of a larger unit. More suitably analogous processes exist in debris flow and rock avalanche studies.

Clast populations examined in an experimental debris flow of pebbles (Major, 1998) are consistent with some of the block arrangements found at peat slides. Transverse orientations at the leading edge of deposits snouts, and parallel/oblique orientations in levees and at deposit margins bear similarity to some of those arrangements seen in peat slides, particularly at Coldcleugh Head and Nein Head 3. Blair (1999) noted a general lack of fabric organization in a large rock avalanche, but observed parallel and oblique (approximately 30°) orientations in levees, where groups of particles had been pushed aside. The multitude of oblique orientations in peat slides may suggest widespread local surging and ebbing across the transporting deposit.

Oblique deposition between distal and lateral margins (of surge waves in debris flows) may occur within peat slide runout. However, the presence or absence of surge waves is difficult to gauge, as clear block-fronted lobes are not visible in the field. Fluctuating block volumes (Figure 5.8) may be associated with compression, break up and subsequent extension of peat masses down-slope, synonymous with surge waves. Surging by compressive and extending flow has been noted by Lewkowicz (1990) for the morphologically similar cases of active-layer slides, although the presence of transverse ribbing in compression has only been noted at Hart Hope (Warburton *et al.*, in press; see earlier in Chapter 4). 'Herringbone clasts', where orientation is almost exclusively oblique to the flow direction, have been noted by McCalpin, (1993), and are attributed to clasts that are checked and diverted from their trajectory by impacts with other obstacles before settling. Such collisions may be frequent occurrences in surging peat masses.

Under fluvial conditions, parallel orientated clasts are associated with high viscosity flows, where solid-solid momentum transfer dominates and clasts are forced parallel to one another (Todd, 1996; Major, 1998). In peat slides, parallel orientations are found in both locally densely and locally sparsely populated zones. In the sparse block areas, low block density may imply high slurry volumes, given the likelihood that slurry is a block product. Associated locally higher viscosities may influence block orientation and produce a tendency towards flow alignment. Such flow alignment is often noted in grain flows (Blair, 1999), and particularly in the fast moving parts of 'frost coated grain flows' (Hetu *et al.*, 1994) which also occur over low slopes, and are suggested as rapid mass movements.

Although the previous discussion shows similarities with other geomorphological systems, attempts to quantify the morphological and morphometric controls on block fabric failed to highlight many significant numerical relationships. This problem is common in clast fabric sedimentology (Bennett *et al.*, 1999; Dreimanis, 1982). Nevertheless, such techniques are regarded as valuable in the interpretation of fluvial deposits (Todd, 1996) and important in the reconstruction of mass failures such as rock avalanches (Campbell, 1989). Attempts to relate orientation to slope angle, produced few conclusive results although scatter in deviation appeared to increase with increasing slope angle, suggesting greater randomness of deposit orientation. This may relate to increased process activity over steeper slopes, and less orderly transport of blocks.

Block dip (or tilt), previously suggested as potentially diagnostic of compression and extension related to wave patterns (Warburton *et al.*, in press) was highly inconsistent in relation to both distance traveled and local block density. There appeared to be some tendency towards outward dip of marginal blocks at Coldcleugh Head and Middlehope, suggesting the barging aside of material by a surging front. Such a process has been highlighted sedimentologically in rock avalanches by Blair (1999). Dip magnitude revealed little dependence on slope. Increased disruption in locally choked block zones was supported by data from Feldon Burn and Nein Head 2, but attempts to relate declining block density to increasing distance, and hence to establish a shift in deposit dominance from blocks to slurry, failed to reveal significant relationships.

5.4.4 The sedimentary significance of peat slide events

With the addition of sediment budget information for the block-mapped sites, the sediment flux was more precisely quantified. While the displaced volumes and quantities delivered were large in most cases (> 4000 m^3), it was more the relative significance of raft, block and slurry through the extent of the slide area that was of interest. The geomorphological significance of each failure is considered in conjunction with post-failure sub-aerial modifications in the following chapter. The implications of source types and hence transport mode is considered here.

Given the following premises:

i) rafts *must* slide, given their extreme plate forms;

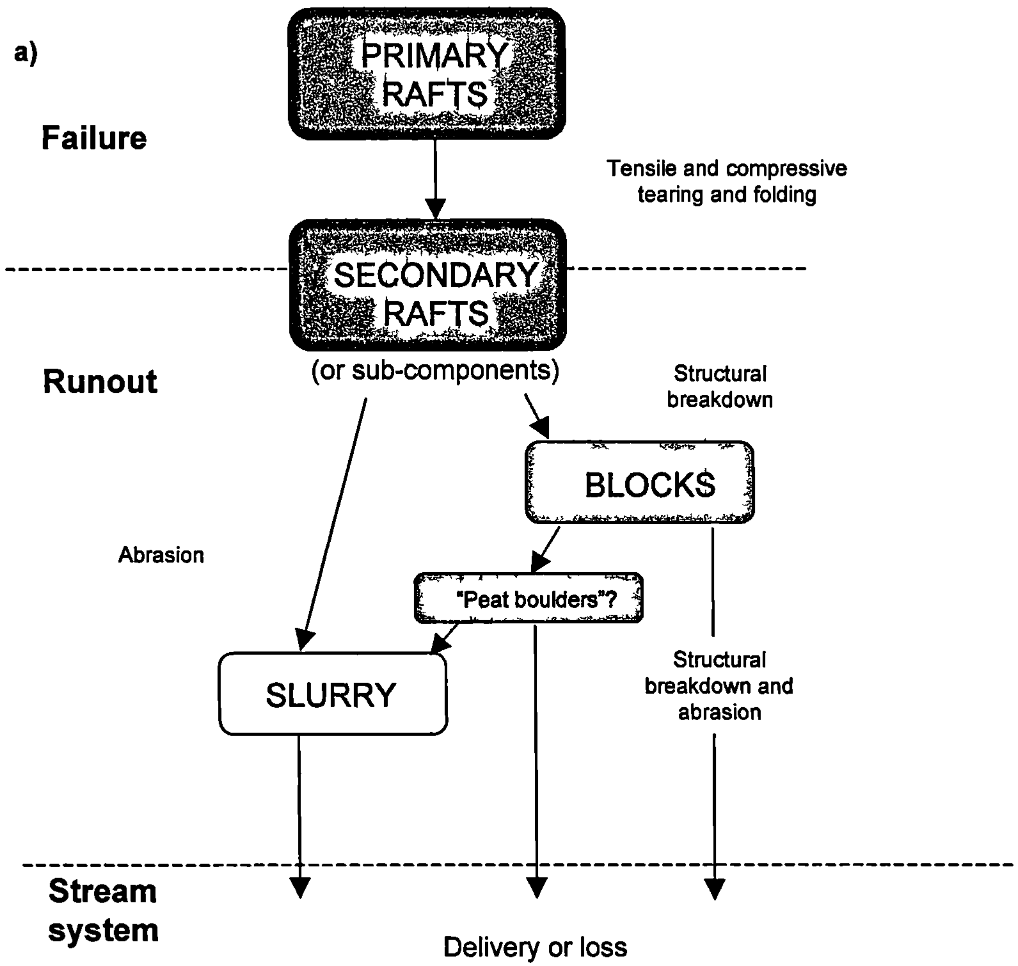
ii) blocks *may* slide or roll, given their range of bladed, spherical and rod forms;

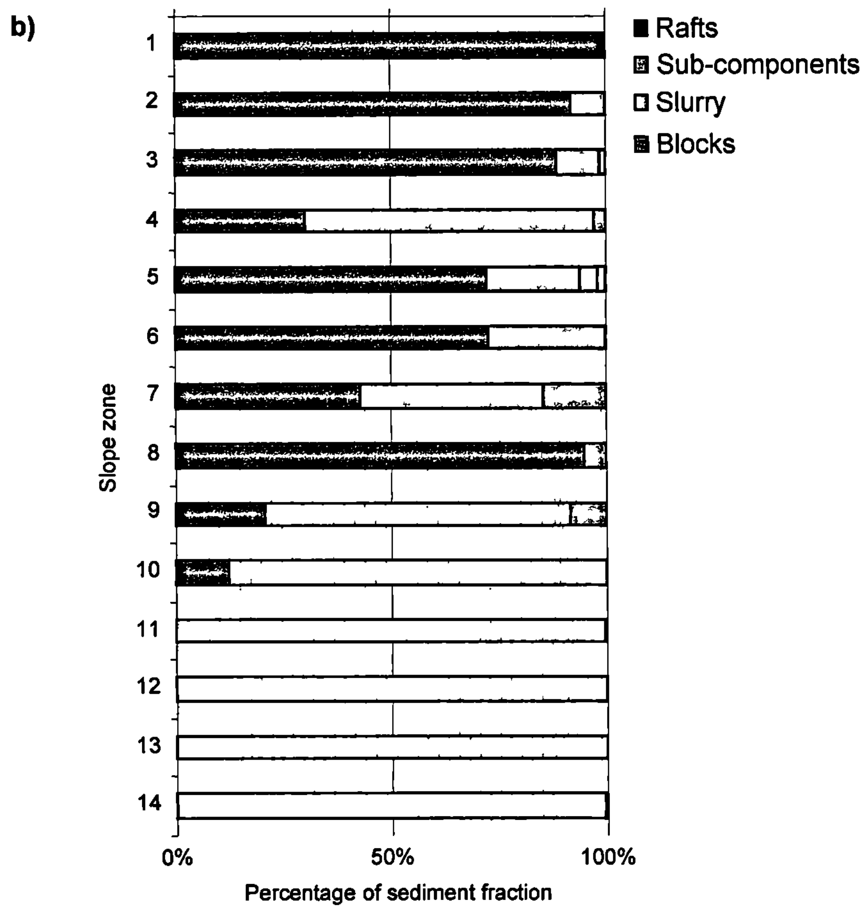
iii) slurry *must* flow, given its probable incoherent, semi-fluid composition.

the relative proportion of each deposit type at any point in the slide zone indicates the dominant process type. Chapter 4 revealed that rafting, where present, occurred almost exclusively in the upper and shallower slopes of slide sites. Hence, material moving from these locations must have moved both slowly (in order to stabilize and be preserved) and *en masse* by sliding. As the sediment budget results suggested, except in the case of very small failures (such as Coldcleugh Head), deposition of blocks increases in significance as the volume deposited by rafting declines. Initially, blocks occupy a greater proportion of sediment deposited than slurry, but rapidly, slurried peat supercedes and accompanies block deposition throughout the remainder of the deposit zone. On this basis, peat slides *do* follow the sequence suggested by Selby (1993), initiating as slab-like debris slides, and after a rapid breakdown of raft forms, continuing as a partially solid, partially fluid debris flow throughout the runout zone. This is formalized in Figure 5.19.

Given that the total area coverage of displaced peat recorded in the field in the form of raft and block top surfaces is usually far below the total area displaced, it is reasonable to assume that much of the former vegetated surface becomes incorporated into slurry. In material terms, those surfaces covered by Sphagnum, or soft mosses with minimal or no roots, are likely to be the peat masses to degenerate first. Unsurprisingly, those slides

Figure 5.19 a) Model of peat slide runout. Boxes represent sediment fractions; b) Distance dependent changes in percentage volume of sediment fractions based on North Pennine peat slide example (Langdon Head). Rafts and slurry dominate process activity.





occurring within established drainage systems (such as Feldon Burn, the lower parts of the Meldon Hill failures, and Middlehope) may contain some of the weakest peat, and these sites often lack significant volumes of blocky or rafted peat.

What is also clear from the sediment budgets is that slurry is the largest fraction of the total deposit at any of the sites that do not exhibit significant rafting. Given that this is the case, the importance of slurry in understanding flow dynamics cannot be underestimated. Future studies would benefit considerably from an assessment of slurry distribution and properties. The material composition of the slurry would significantly elucidate its origins. A mainly fibre-less slurry would suggest predominantly basal sourcing, while locally fibrous slurry (with turf mats) would indicate block disintegration. The spatial distribution of the slurry, particularly with respect to its depth, would provide valuable information with regard to the rate of slurry generation downslope.

The presence of a pre-existing rather than remoulded peaty slurry at the base of bog bursts has been alluded to by a number of authors in the field of peat mass movements (see Chapter 2, section 2.2.2). In peat slides, sediment transport has more regularly been associated with sliding (Johnson, 1992), with occasional reference to debris-flow processes in the lower slopes (Crisp *et al.*, 1964; Carling, 1986). The highly humified nature of basal peat at slide sites (See Chapter 3) suggests that on movement, remoulding may rapidly destroy peat structure and produce a cohesionless slurry. The implications are, that while remoulding by shearing forces at the base of rafts and blocks continue, these solid masses will move upon the slurry that they generate, and within the slurry generated by other more broken down blocks. Such a two layer system, where stronger material with limited deformation overrides weaker and thinner mobile layers, may be referred to as a 'composite flow' (Hungr, 1995). Such flows are frequently described by clastic sedimentological approaches, in which velocity gradients set up between the surface and sub-surface deposit components determine the degree of orientation of the surface or buoyant clasts. Lewkowicz (1990) has referred to this layer as the 'shear zone' in active layer slides, which are similar on morphology to peat slides. Highly deformable basal layers have also been associated with lubrication (Campbell, 1989) and hence long runout, and vertical velocity gradients, leading to both buoyancy and inverse vertical grading in debris flows (Todd, 1996), as well as maintenance of sliding in active-layer slides (Harris and Lewkowicz, 1993).

As blocks abrade and peat block depths decline, the remaining structurally coherent blocks, often fibrous in nature, will impart greater resistance to the surfaces over which they travel, increasing their likelihood of deposition. Equally, block and slurry depths will approach unity relative to one another as the slurry supply becomes limited, and the peat mass as a whole is more likely to behave as an homogenous, highly viscous fluid. Only at this point may the slide be considered rheologically homogenous enough that sediment-water flow approaches might be applicable. However, by this time, much of the deposition has already taken place. It is beyond the scope of this chapter to investigate potential rheological relationships in the peat slurry.

In summary, the available evidence suggests that once movement has initiated by translational failure, block mass degeneration is rapid. Unless rafted peat stabilizes rapidly, breakdown of the peat mass follows. This occurs simultaneously across and down-slope as rafts fragment and abrade in transport, leaving blocks and slurry in their wake. As blocks continue to travel down-slope, they either abrade and stabilize or roll and fragment further, with slurry continuing to dominate. Eventually, when a critical flow depth is reached, slurry is no longer able to flow, blocks stabilize and runout ends. The suggested sequence of movement is as follows (Figure 5.19):

i) after initial break-up by sliding, rafted masses rapidly fragment into parallel, elongate sub-rafts. These either become stranded in low-slope, upper sections of the scar, or accelerate, orientating oblique-parallel in the dominant flow direction;

ii) sub-rafts and blocks travelling down-slope may either enter free-flow over the planar, undisturbed blanket surface, or become constricted by other stabilized peat mass, or within channels;

iii) the peat block/slurry in free flow over planar surfaces may move by local surging, with rafts acting as surge fronts, and blocks breaking away from the back of rafts during acceleration;

iv) in zones of compression and deceleration, blocks orientate oblique-normal to flow, while in zones of extension and acceleration, they orientate oblique-parallel to flow; local surges *may* be governed by a wider kinematic wave motion in slides long enough for such a mechanism to generate;

v) the peat block/slurry mixes in confined flow within channels and local depressions orientate parallel to the flow direction, and are rapidly reduced in size during transport, or are deposited;

vi) in both cases, continual block-to-block collisions, abrasion, and internal structural weaknesses act to reduce block sizes with increasing transport distance;

vii) the peat mass stabilizes when blocks abrade their bases until more resistant surface structures remain. These increase friction, and when slurry supply is limited to the extent that internal shear strength exceeds the impulse to move downslope (at approximately 0.12 m depth), deposition occurs.

Any of these stages may be cut short where sediment enters local channel systems. In such cases, block and slurry transport becomes fluvially determined, and process types and rates may adhere more closely to those described by Evans and Warburton (2001). Under such conditions, blocks may settle temporarily on channel bars and channel margins (Warburton and Higgitt, 1998) before ultimately been washed away by subsequent channel events.

The rates of movement with respect to all these processes will be dependent upon both the masses of material involved, the slope forms and lengths, and the fluidity of the transported peat mass (although it will be very high in all cases). Earth and debris slides may travel at up to 16 m s^{-1} in granular materials (Corominas, 1996), while debris flows may vary in velocity from slow, viscous movements (10^{-8} m s^{-1}), to very rapid, more fluid flows (10^{2} m s^{-1}) (Pierson and Costa, 1987). It is difficult to relate these velocities to peat slides and flows, given the differing material compositions and the relatively low slope angles over which they occur.

5.5 Chapter summary

This chapter has described the spatial distribution of deposit elements formalized in chapter 4, and related this distribution to deposit characteristics indicative of geomorphic process activity. Rafted deposits, considered primarily in the previous chapter, appear to be morphological precursors to blocks. Blocky debris is the most spatially widespread deposit, and provides evidence of process extent in the deposit track once slurry has been washed away. Deposition of blocks indicates generally chaotic transport, with inherited form rapidly lost on break-away from rafts and scar margins. Their distribution, and tendency to orient and dip suggest local compression and extension, giving zones of high block density and areas largely absent of blocky deposit. Slurry appears to be a product of both block breakdown and raft and block basal abrasion. Intermediate secondary rafts (or sub-components) and peat-boulders provide transitional forms of deposit between the extremes of deposit size and coherence that rafts and slurry represent. Although blocks and rafts provide the major evidence of sedimentation at older peat slide sites, the slurried volume which is washed away in the aftermath of failure, probably represents the most significant volume of deposited material at most failures. Deposit evidence at most sites is insufficient to establish the spatio-temporal controls on a change from predominantly solid mass transport to more fluid, debris flow-like transport. However, there appears to be a tendency towards sliding in the upper scar, and flowing in the lower track. Raft evidence and photographic evidence suggest peat blanket break up is usually complete before the disturbed material reaches the lower scar limits, and that slurry accompanies solid transport within the scar area and beyond.

6 THE MATERIAL CHARACTERISTICS OF FAILED PEAT MASSES

6.0 Introduction

The material characteristics of peat have received little attention in past investigations of peat slides, and bog bursts. Uncertainty over the position of the failure plane, or shear zone has precluded laboratory investigations of micro-scale material characteristics, such as shear strength. At peat slides, evidence largely based on morphology suggests a translational failure mechanism operating at or beneath the interface of peat and substrate. Such an assumption has formed the basis for studies of slope stability at peat slide sites (e.g. Carling, 1986; Dykes and Kirk, 2001). Bog burst morphology has suggested a 'quick' failure, in which the peat may be regarded as equivalent to a 'sensitive' soil (Selby, 1993). Sensitive materials may remain stable for thousands of years, yet suddenly lose strength, often catastrophically with little or no increase in moisture content and low applied stress. Such 'quick' failure in peat has not been considered in discussions of failure mechanism, despite the morphological similarity of quick clay failures to bog bursts (section 2.3.2). Investigation into the material controls of bog bursts has yet to be undertaken at more than a speculative level.

This chapter aims to clarify ambiguities relating to peat slide failure mechanisms, through an understanding of intrinsic material controls. Attention focuses on identifying the most likely plane of failure within the displaced mass as a whole, on the basis of both geotechnical and stratigraphic approaches. Material sampling and testing frameworks are designed to accommodate as far as possible the full range of hypothesised failure mechanisms outlined in Chapter 2. While geotechnical testing procedures are incorporated in the analysis, their scope is such that they represent a starting point (or pilot study), rather than an end point for the better understanding of failure mechanisms. Extrinsic factors such as climatic conditions are not directly considered, because it is the properties of the peat mass that ultimately control the initiation of movement, and because climatic records relating to peat slide initiation are too superficial to allow focus to an explanatory level, such as in the consideration of thresholds of triggering rainfall (e.g. Caine, 1980; Crozier, 1999).

Hypothesis generation with regard to peat mass properties was limited in Chapter 3 by the scarcity of data in the established literature. Hence objectives within this chapter reflect the issues identified in Chapter 2. These aims are as follows:

i) to define the stratigraphy which is typical of the blanket peatland in which North Pennine peat slides occur;

ii) to characterise the material properties of these stratigraphic units, in terms of their bulk and mechanical properties;

iii) to evaluate the influence of these properties in promoting stability or encouraging failure within each stratigraphic unit;

iv) to re-evaluate previously hypothesised failure mechanisms in the light of objectives i - iii).

Unlike bog bursts, peat slides usually incorporate some of the substrate in the failed mass. At initiation, the extent to which this occurs is unknown, although it has been suggested by a number of authors (Carling, 1986; Acreman, 1991; Dykes and Kirk, 2001) that failure is controlled by substrate strength, not peat strength. A weakness in these previous studies has been to assume failure within the substrate, and to investigate only substrate properties in detail. The bulk properties and engineering characteristics of the two material bodies, as well as the nature of their contact, determine their likelihood of failure.

In the field, these materials occur in undisturbed and disturbed states. Disturbed material in the scar margins is torn, compressed and thrust from its original position, dried or saturated by alterations in its hydrology, and is the material disconnected, transported and distorted during runout. Although the disturbed material has been directly involved in failure, it is likely to be unrepresentative of its pre-failure state because of the forces to which it has been subjected. The requirement to understand material properties leading to failure necessitates the use of material from the undisturbed peat and substrate mass (Rogers and Selby, 1980; Craig, 1997). Undisturbed materials are found surrounding the exposed slip surface. Only the materials that have been unaffected by tensional and compressional forces, and which have not experienced significant drainage since failure are truly undisturbed.

Hypotheses pertinent to failure may be formulated, based upon available material evidence. Published reports of peat slide occurrence in Chapter 2 have suggested failure within the substrate, the peat-substrate interface, and the peat mass itself (in decreasing frequency of report). Chapters 2 and 3 suggested that peat slides and bog bursts differ in their basal peat characteristics ('sensitive' behaviour specific to peat at bog bursts). Morphological information in Chapters 4 and 5 has suggested that material characteristics of the peat mass may control deposit break-up during movement. Given these assertions, the following hypotheses apply, and may be tested:

i) there is a clear hierarchy of material strength exhibited at peat slide sites, in which the substrate is the weakest, the peat-substrate contact is of intermediate strength, and the peat mass the strongest;

ii) heavily rafted sites (see Chapter 5) result from peat with higher internal strength than non-rafted sites;

iii) peat slide and bog burst materials show consistent differences in bulk properties.

The focus of analysis in this chapter is peat slide material characteristics. However, peat materials have also been examined at the Glendun bog burst, Co. Antrim in Northern Ireland, and these are considered in Chapter 8 with other aspects of bog burst morphology, mechanism and recovery. The following sections consider sampling strategy and the methods employed in the light of available material evidence at the slide sites under study. Results are described and evaluated in the context of the peat failure literature, more general studies of peat material properties, and wider considerations of landslide failure mechanism.

6.1 Methodology

The definition and characterisation of layers within the failed profile requires sampling as close to the scar head as practicable, from the peat into substrate. Similarly, downslope variations in material properties (adjacent to the predominantly linear scars) require sampling of material from the scar flanks. Morphological evidence suggests a failure plane centred around the peat-substrate contact (Chapter 4, section 4.3; Carling, 1986; Warburton *et al.*, in press). In some cases this contact may be graded, and hence a *transition*, and in other cases, peat and substrate may be discontinuous, and hence a boundary or *interface*.

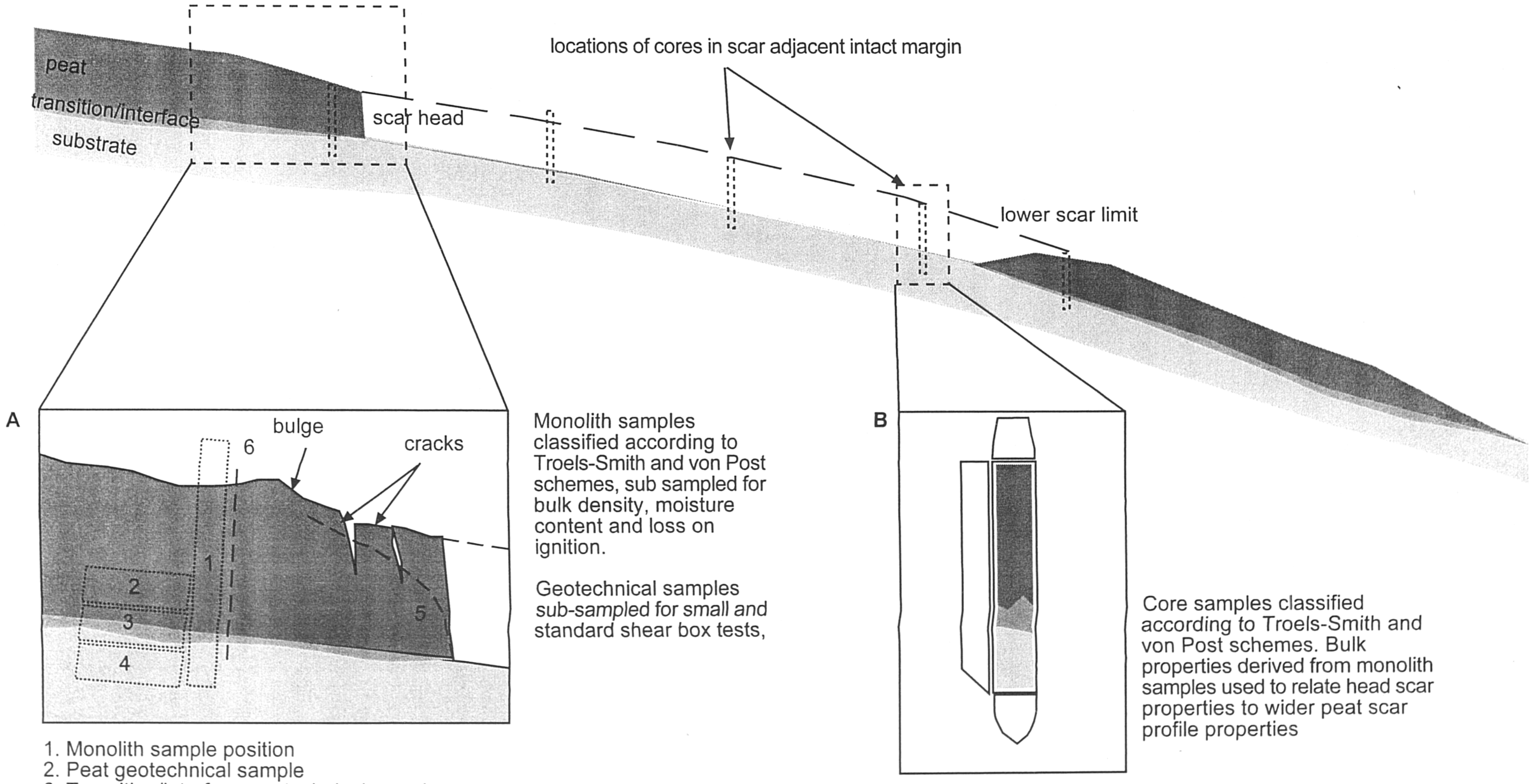
The type of peat-substrate contact, and the peat depths at different sites are likely to be variable. Breadth and depth in sampling is required to provide a sound understanding of material characteristics for the full North Pennine slide population. It has been noted that geotechnical laboratory tests are both resource intensive, and a poor basis for comparison with the limited studies undertaken at non-Pennine peat failures. Nevertheless, engineering properties are standard requirements for the study of slope stability in mineral materials, and must be considered. Stratigraphic techniques provide a detailed description of changing profile properties with depth, as well as a good basis for comparison with other published peat failures, but are a poorer quantification of material strength than geotechnical characteristics. Bulk material properties, such as bulk density, moisture content and organic matter content represent a suitable intermediate source of information. Bulk properties have been shown to relate clearly to aspects of the peat mass described by stratigraphic methods (such as humification, fibre content; Wilson, 1972; Galvin, 1976; Landva *et al.*, 1983; Hobbs, 1986), and also to geotechnical characteristics such as consistency (Atterberg) limits and compressive strength (Wilson, 1972; Hobbs, 1986). They may also be derived relatively rapidly and with smaller sample quantities than can geotechnical parameters.

6.1.1 Field sampling framework for determining peat slide material characteristics

Detailed geotechnical approaches were combined with broader at-a-point stratigraphic sampling using cores, and bulk property assessments derived from monolith samples, as shown in Figure 6.1 and Table 6.1. This permitted regional assessment of material characteristics across all sites, site-wide and profile based sampling at each slide, and micro-scale assessments at one site, the Hart Hope failure. Hart Hope is the most recent North Pennine failure (1995; Warburton and Higgitt, 1998) exhibiting characteristic peat slide morphology. Of the North Pennine population, its material characteristics are the least likely to have altered since failure. Hence it represents the optimum sample site for detailed geotechnical assessment of materials.

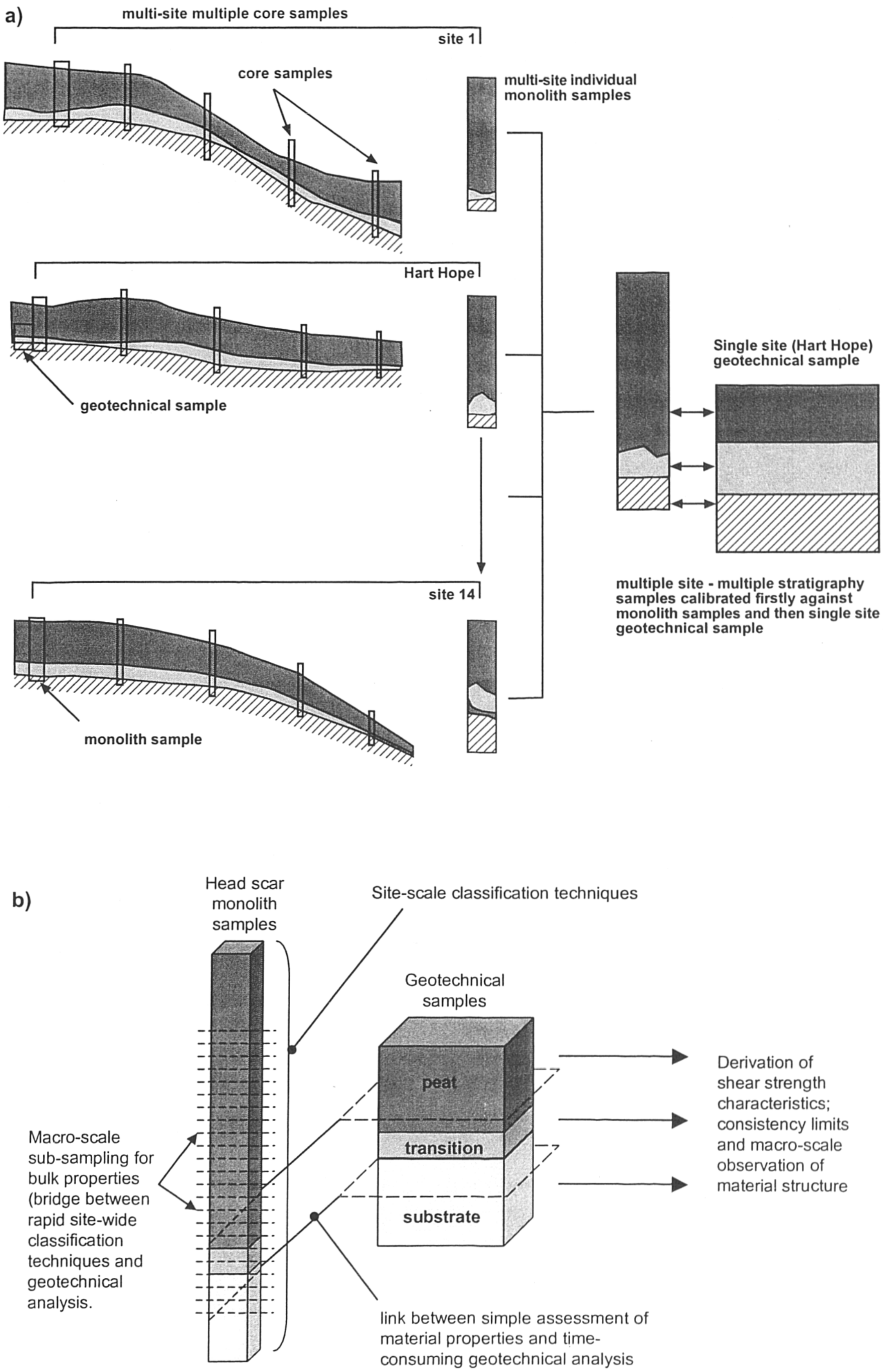
Geotechnical properties at Hart Hope are related to bulk properties derived from profile samples at the head scar ('A', Figure 6.1; Table 6.1) using previously published empirically derived relationships (e.g. Landva and Pheeney, 1980; Hobbs, 1986; Bell, 2000). Stratigraphies taken for the same profile samples allow bulk properties to be related to rapidly assessed visible characteristics of the peat and substrate, such as fibre content,

Figure 6.1. Sampling framework for understanding of material controls on peat slides



1. Monolith sample position
2. Peat geotechnical sample
3. Transition/interface geotechnical sample
4. Substrate geotechnical sample
5. Limit of hydrological disturbance caused by water table drawdown at exposed face
6. Limit of physical disturbance caused by cracking and bulging

Figure 6.2. Sampling framework for material analysis at peat slide sites. a) multi-site to single-site samples at Hart Hope; b) monolith and geotechnical subsampling.



humification and texture. If stratigraphic units can be followed from the scar head profile samples throughout the scar-adjacent cored samples ('B', Figure 6.1; Table 6.1), then bulk properties may be extrapolated with reasonable confidence throughout the extent of these units. Figures 6.2a and b illustrate how bulk properties and stratigraphic methods are associated with larger geotechnical samples.

	Classification		Bulk properties					
	Troels-Smith	Von Post	Wet bulk density	Dry bulk density	Weight moisture content	Volumetric moisture content	Loss on ignition	Particle size
Peat (monolith)	✓	✓	✓	✓	✓	✓	✓	
Transition/ interface (monolith)	✓	✓	✓	✓	✓	✓	✓	
Substrate (monolith)	✓	✓	✓	✓	✓	✓	✓	
Peat (geotechnical)			✓		✓		✓	
Transition/ interface (geotechnical)			✓				✓	
Substrate (geotechnical)			✓		✓		✓	✓

Table 6.1. Test matrix for investigating bulk properties, engineering parameters and available techniques

As noted in the previous section, undisturbed materials available for investigation surround the scar perimeter. Constraints were placed upon sampling locations according to the following criteria:

i) the sample location should be as central to the head scar as possible (after Rogers and Selby, 1980);

ii) the sample location must have retained hydrological connectivity with the intact blanket peat above it;

iii) it must be possible to assess the context of the sample location to a minimum of 1.5 m to either side of the point of extraction (after Barber, 1981);

iv) the extracted material must be as undisturbed as possible to ensure that physical properties are not altered from their natural state (after Craig, 1997).

Both the scar margins and the below-scar intact blanket were avoided, given the likelihood of lateral compression and overriding by the transported peat mass at these locations. Thus, geotechnical samples were extracted as close to the central axis of failure as possible towards the scar head (see Figure 6.1).

Coring was undertaken in transects parallel to the scar downslope axis in the undisturbed peat on the least disturbed lateral scar margin. Samples were collected 3 m back from the scar margin to avoid the effects of changes in water table associated with draining of the scar sidewalls.

The following three sections describe the rationale for stratigraphic, bulk property and geotechnical tests for the slide population from regional to micro-scale.

6.1.2 Rationale for stratigraphic assessment of peat and substrate properties

In mineral sediments, textural classification based upon the relative proportions of clay, silt and sand-sized particles is usually regarded as basic to the characterisation of an earth material (Rowell, 1994; Craig, 1997, Brady, 1999). This is not possible for peat. Instead, in engineering terminology, peat is regarded as comprising two materials: fibres and filling (Silfverberg, 1955; Sellmeijer, 1994). The filling or matrix is considered by many as clay-like (Landva and Pheeney, 1980; Hobbs, 1986), while the fibres are more as vegetative structural components than a part of the peat 'soil' (Boelter, 1969; Fox and Edil, 1994). The relative importance of the fibres and matrix is dependent upon the degree of decomposition (or humification) of the vegetation. The von Post (1924) scheme is generally used to this end, employing humification as a basis for classification. Humification is quantified by the field worker according to a number of descriptive criteria. Several volumes of the Proceedings of the International Peat Congress (e.g. IPC 3rd, 1968; IPC 4th, 1972 and IPC 6th, 1980), along with key papers by Radforth (1956; MacFarlane and Radforth, 1968) have debated modification and supplements to the basic scheme, yet it is used, largely unaltered in geomorphology, Quaternary studies, and even some engineering studies (e.g. Landva and Pheeney, 1980; Hobbs, 1986; Head, 1988).

While Hobbs (1986) advocates the use of a modified von Post system (after Landva *et al.*, 1983) incorporating a greater degree of quantification, this is only sufficient for consideration of peat alone. Given the mineral inputs highlighted earlier (e.g. soliflucted clay), and the requirement of this work to examine the nature of the peat-substrate contact and substrate itself, a combination of both von Post and the Troels-Smith (1955) scheme is proposed. The Troels-Smith scheme is based upon structured estimates of the relative quantities and types of mineral and organic sediments, vegetative structures, and the nature of contacts between successive layers of sediment. In combination with the von Post system, a structured description, classification and initial characterisation may be produced for sediment examined in the field or laboratory.

6.1.3 Rationale for laboratory determination of bulk properties

Weight and volume relationships are the simplest summaries of the physical properties of a material. Volume parameters for the three phases of solid, liquids and gas may be combined with weight parameters for the same three phases to produce measures of material bulk properties (Skaven-Haug, 1972). The density of a material is summarised in its bulk density (ρ), which is the ratio of total wet (natural/field) or dry mass to total volume, and which is expressed as kg m^{-3} or Mg m^{-3}. The bulk density of water is 1000 kg m^{-3} (1 Mg m^{-3}), and the bulk density of peat usually falls slightly above this (Boelter, 1968; Galvin, 1976; Hobbs, 1986; Bell, 2000). Bulk density is the most frequently cited bulk property of peat (and substrate) in mass movement studies (e.g. Alexander *et al.*, 1986; Carling, 1986; Hendrick, 1990; Wilson and Hegarty, 1993; Dykes and Kirk, 2001; Warburton *et al.*, in press), however values are not readily comparable given the use of dry bulk density in some studies, and wet in others. This study will derive both wet and dry bulk densities for all samples used.

The physical and engineering characteristics of peat are profoundly influenced by its water content. Peat properties that depend upon water content include wet bulk density, degree of saturation, consistency limits, shrinkage and shear strength (Hobbs, 1986). Excessively high water contents in the basal layers of peat masses, and below, are usually cited as implicit in failure initiation (Hemingway and Sledge, 1941-46; Acreman, 1991; Selkirk, 1996; Wilson *et al.*, 1993). While some peat failure studies have recorded moisture contents (e.g. Alexander *et al.*, 1986; Wilson and Hegarty, 1993), its determination is by no means standard. In order to provide a more complete representation of layer properties, moisture contents are also derived for North Pennine failures. While it is acknowledged that these will not be representative of moisture contents at the time of failure (which would likely be higher), the relative saturation of successive layers may provide an indication of the relative moisture content. Skaven-Haug (1972) has noted the misleading nature of moisture content calculations by weight alone for the comparison of mineral and organic sediments. Consequently, both weight moisture contents (for comparability) and volumetric moisture contents are calculated for all samples.

Finally, where mineral layers are important and where the peat-substrate boundary is to be considered, organic matter content may be a valuable indicator of sediment profile characteristics and engineering properties (Bell, 2000). Organic content may be determined by chemical analysis (e.g. Ball, 1964; Skempton and Petley, 1970), but this is only suitable for materials with low organic matter content (Hobbs, 1986). Rather, calculation of ash or mineral content (and hence, organic matter by subtraction) is made by loss on ignition. Where clay minerals are present, excessive temperatures may give rise to loss of fixed water giving erroneous values. While Galvin (1976) suggested the use of temperatures not greater than 500°C in order to avoid this, a value of 450°C is quoted by Hobbs (1986), and a value of 375°C by (Ball, 1964). Erring on the side of caution, samples collected from North Pennine sites, known to be rich in clay minerals are subjected to 375°C burns only.

6.1.4 Rationale for laboratory determination of geotechnical characteristics

At peat slides, the shear zone/failure plane represents the material layer in which a threshold of slope stability is exceeded and failure initiates. The dominant geotechnical properties used to characterise shearing of earth materials are the consistency limits and shear strength parameters (defined in Appendix 2). The former describe whether the material behaves as a solid, semi-solid, plastic or liquid. They are dependent upon moisture content, such that increases in moisture cause the material to change from a solid to a liquid state (Selby, 1993; Craig, 1997). The shear strength parameters, ϕ and c, are quantified factors in describing the resistance of materials to shearing forces. Shear strength is controlled by its bulk and engineering properties, and determines the susceptibility of a material to failure. The consistency limits and shear strength parameters for peat are poorly understood with respect to mineral material, and the following description incorporates a brief review of the conceptual difficulties associated with their use in peat.

In mass movement initiation, it is the plastic and liquid states of the material that determine type and rate of deformation. For a material to display plastic behaviour (undergo unrecoverable deformation at constant volume without cracking or crumbling; Selby, 1993), it requires the presence of clay. In peat, the greater the decomposition (or humification), the less this clay fraction need be (Hobbs, 1986). In its fibrous state or without any clay component, plasticity tests cannot be conducted on peat (Akroyd, 1964). Even where the tests are conducted, they correlate poorly with other bulk and mechanical properties, and shed little light on controls over geotechnical behaviour of peat (Hobbs, 1986). The liquid limit has received little attention in peat (e.g. Hanrahan, 1954; Galvin, 1976; Eggelsmann *et al.*, 1993), but considerable attention in clay materials (e.g. Bjerrum, 1957). For example, the liquid limit has been used to assess the sensitivity of marine clays to quick failure, and to determine tendency towards strain softening (Torrance, 1987). Values available for the liquid limit of peat suggest it is far higher than for clays - ranging between 800 and 1500% for well humified bog peats. The liquid limit declines with increasing humification (Hobbs, 1986) such that moisture contents need not be excessive for the peat to behave as a fluid. Sudden changes from semi-solid or plastic states to liquid behaviour may be more relevant to sensitive quick failure (bog bursts) than to shear failure (peat slides). Furthermore, sampling preparation for liquid limit tests involves the break-up of soil structure, which in fibrous peaty material may be critical to its strength characteristics. Liquid limit tests are only undertaken on the mineral substrate, because of the lack of comparable data from other peat slide studies, and the conceptual difficulties associated with the test for peat.

Shear strength parameters provide the other geotechnical data required to examine slope stability. At any point on a slope, if the applied shear stresses (parallel to the ground surface) equal the material shear strength, then failure will occur. The idea of shear strength was originally proposed by Coulomb, with τ_f (shear strength at failure) expressed as a linear function of normal stress at failure (σ_f) over failure the plane (Craig, 1997):

$$\tau_f = c' + \sigma_f' \tan \phi' \qquad \ldots \qquad \text{Equation 1.}$$

where *c'* and ϕ' are shear strength parameters in terms of effective stress, and are the cohesion intercept and the angle of shearing resistance (or angle of internal friction) respectively. The cohesive strength of materials containing clay is a function of electrostatic bonds, material cementation and water content. In pure clays, this may be considerable (Selby, 1993; Craig, 1997). In peat, opinion is varied (e.g. Ward, 1948; Hanrahan, 1954; Hardy, 1968; Helenelund, 1972). It mainly depends on the role played by fibres, which provide an apparent cohesion in the form of an anisotropic tensile strength (Wilson, 1972; Helenelund and Hartikainen, 1972; Landva, 1980).The importance of these micro-structural fibre properties in controlling the values of ϕ and c has been poorly quantified.

The angle of shearing resistance represents the angle under which the material structure is stable. In mineral soils, friction is a product of inter-particle contact, averaged through the plane of shearing. In pure peat, the lack of minerals leads to a different form of frictional contact, based upon cell-to-cell contacts. Frictional resistance increases to a point determined by the strength of individual cell chambers, which after collapse, release cell water into surrounding void spaces, reducing friction and simultaneously increasing pore-water pressures (Wilson, 1972). The complexity of this peat specific mechanism remains essentially untested. The concepts of pore water pressure are dealt with in Terzaghi's (1936) extension of Coulomb's (1776) work, which considers effective shear strength parameters. Here, effective stress is a product of the difference between applied normal loads and the response to them generated by pore water pressures. Increasing pore water pressures act to push particles apart, reducing the shear strength of the soil.

When considered above the microscopic scale, the shear strength parameters of the larger material mass are only representative where the test conditions correspond to field drainage conditions. For clays, silts and sands, shear strength may be determined in laboratory conditions through the use of direct shear and triaxial tests on samples returned from the field (Head, 1982; Bromhead, 1986; Craig, 1997) or using the vane shear apparatus within the field (Head, 1982). The results of the tests depend primarily upon the material characteristics, the quality of the sample (disturbed versus undisturbed) and also on the loading and moisture scenarios under which they are tested (Vickers, 1983; Craig, 1997). When compared with inorganic materials, there is a lack of information on peat and interface material shear strength tests. In the case of peat, a limited number of publications describe tests using most of the available methods (see Table 6.2). The peat types and testing scenarios often vary considerably between studies. There has as yet been no satisfactory collation of shear strength data for peat, either in the most detailed of peat

Table 6.2. Examples of previously published apparatus used in the derivation of shear strength parameters for peat.

		Available loading, drainage and test scenarios				Sample requirements	
Apparatus	Variant	Drainage scenarios	Loading scenarios	Residual Strength	User defined failure plane	Number of samples to derive angle of internal friction and cohesion	Sample dimensions (mm)
Shear box	Large	drained, undrained	high to moderate loads	yes	yes	3	305 x 305 x depth
	Standard	drained, undrained	low to moderate loads	yes	yes	3	98 x 98 x depth
	Small	drained, undrained	low to moderate loads	yes	yes	3	60 x 60 x depth
Triaxial	not applicable	drained, undrained	cyclic	no	no	1	38-254 mm (diameters) x 76-500 mm (heights)
Ring shear	not applicable	drained, undrained	low to moderate loads	yes	yes	3	dependent on individual machine specifications
Shear vane	not applicable	cannot be defined	none	yes	yes	not applicable	not applicable

mass studies (e.g. Hobbs, 1986; Heathwaite and Göttlich, 1993; den Haan *et al.*, 1996) or in the most recent available summaries (e.g. Bell, 2000). Interface materials have rarely been tested.

The contrasting merits of the equipment available for measuring shear strength are shown in Table 6.2 with respect to sample size and test ranges. Shear boxes are suitable for interface testing (particularly with increasing size of apparatus), are easy to use and produce results rapidly, and are suitable for residual strength tests (Head, 1982). Disadvantages stem from the unequal distribution of shearing forces across the pre-determined failure plane, the limited strains possible within a single shear stage and the lack of control over drainage and measurement of pore water conditions (Vickers, 1983). Triaxial cells provide the greatest control, but sample dimensions and test procedures are such that shear planes cannot be pre-determined, and thin horizontal layers in which failure may occur are not suited to the required sample dimensions. The generation and assessment of shear planes is a key concern in the context of this research. The vane shear test is most suited for soft sensitive soils which cannot be returned to the laboratory because of the effects of sampling disturbance. Landva (1980) suggested that shear vanes should not be used in the study of either amorphous or fibrous peats due to a lack of consistency in results. The ring shear apparatus is of limited application (Head, 1982) and has not been used for testing in peat failures.

Previous attempts to determine shear strength for peat slide substrates (Carling, 1986; Dykes and Kirk, 2001) cite increased pore water pressures as the most likely cause of failure. However drained-consolidated shear tests are used in their analysis. These tests do not simulate the conditions postulated for failure.

It is proposed that a range of tests is conducted incorporating drained and undrained scenarios, and on the three material layers found at slide sites - peat, interface and substrate. These are supplemented with liquid limit and plastic limit testing of the mineral substrate.

6.1.5 Sampling and method for stratigraphic assessment of peat and substrate material properties and determination of bulk properties

At the sampling locations, peat at the scar surface was cut away to produce a vertical face across a 3 m span. A field log of the face was conducted according to Barber's (1981) conventions for palaeo-ecological sampling of peat, noting i) stratigraphic boundaries and ii) depths and arrangements of laminations. In addition, a photographic and written log was recorded (according to Hodgson, 1976) taking into consideration i) date and time; ii) weather conditions; iii) spatial location of sample; iv) microrelief; v) aspect; vi) surface vegetation and vii) evidence of hydrological significance, namely seepage and/or pipes (Gilman and Newson, 1980).

Monolith samples were collected by pressing tins lightly into the peat face, and then cutting into the peat with a sharp knife along the impression of the tin. This technique, following procedures suggested by Millette and Broughton (1986) and Stoodley (1998) enabled the tins to be pressed fully into the peat avoiding compression, or distortion at the tin margins (Hobbs, 1986; Brown *et al.*, 1984). The tins were then separated from the peat blanket by cutting behind the tin, with the excess material removed before samples were sealed. In addition, a small bagged sample of each stratigraphic unit was collected from the face to supplement the monolith samples.

Due to time constraints, core stratigraphy could not be fully logged in the field, and full profiles were retrieved and returned for storage. Again, for practical reasons, not all cored locations could be sampled, and where breaks in sequence were necessary, the nature and depth of the peat-substrate interface was recorded. Where sampling was undertaken, 0.5 m cores were extracted sequentially using a Russian closed-chamber corer (Aaby and Berglund, 1986) until mineral substrate was sampled and a full profile achieved. Cores were placed in plastic half piping, sealed and returned to the laboratory for analysis. All core locations were surveyed in relation to one another and to the scar margin.

The monolith samples were classified according to the modified von Post and Troels-Smith schemes before being sub-sampled for material properties. The following bulk properties were evaluated:

i) wet and dry bulk density;

ii) moisture content by weight and volume;

iii) organic matter content by loss on ignition at 375°C.

Monolith samples were sub-divided into 3 cm 'deep' slices (Figure 6.2b). Because samples were to be examined at field moisture content and fully dried, a sample size of 3 cm represented the minimum slice depth, which after shrinkage, would still permit a structurally coherent mass to be used in dry volume calculation.

Each slice was cut to uniform dimensions, measured and then weighed at its natural moisture content. Samples were then left to air-dry to avoid charring, re-measured and re-weighed. Dry volumes were calculated by submersing them in water within graduated measuring cylinders. Peat samples were tapped against the cylinder sides to shake out trapped air bubbles.

In order to establish the relationship between qualitative evaluation of material type (using von Post and Troels-Smith), semi-quantitative representation of layer properties and quantitative assessment of bulk properties, all datasets were entered into Tilia 2.0™ software. TiliaGraph™ and TiliGraphViewer™ were used to provide a graphical representation of stratigraphy. The semi-quantitative estimates of darkness, plasticity, boundary strength and stratification (from Troels-Smith), along with assessments of fibre and wood remains and humification (via von Post) were represented as blocked plots in columns adjacent to the stratigraphy. Finally, the bulk properties (wet and dry bulk density, volumetric and weight based moisture content, loss on ignition) were plotted as line graphs.

The variability of the material profile and the strengths of discontinuities within it were evaluated via constrained cluster analysis, using the CONISS™ package attached to Tilia 2.0™. On this basis, the major stratigraphic discontinuities can be determined numerically in addition to qualitatively, and the justification for perceived discontinuities within the peat and at the transition-substrate quantified.

Cores were classified according to the modified von Post and Troels-Smith classifications only. This information was again fed into Tilia 2.0™ and processed with CONISS™ though without bulk property information. Each stratigraphy was plotted according to its position on its scar-parallel transect, and major and minor boundary locations marked.

6.1.6 Sampling and method for determination of geotechnical characteristics

Geotechnical samples for the derivation of shear strength parameters were taken from the

Hart Hope site only. Large box samples (22.5 x 21.5 x 8 cm) were extracted spanning a sequence of material from basal peat into substrate (shown in Figure 6.1 'A'). The samples were taken from the material behind the face used for monolith sampling to provide a reference stratigraphic context. Blocks were 'cut' out of each layer using sharp knives and sample tins placed over the blocks. The samples were then separated from the ground by cutting underneath, and tin orientation and position labelled.

It was not possible to take a continuous sample from top to bottom in either of the two 'columns' due to the presence of large clasts in the substrate. These interfered with the cutting of sample blocks, and would not yield testable sub-samples under laboratory conditions. However, all samples were located within approximately 1 m of one another, and samples of the same-type were located at the same depth relative to the original surface.

In the laboratory, sub-samples were carefully cut from the large box samples using a cutting tool and scalpel, ensuring that the samples did not fracture or contort. Substrate samples were extracted with relative ease from the larger box samples, although significant amounts of each box sample could not be used due to the presence of large clasts. Similarly, the large peat samples yielded sub-samples of consistent size and of apparently similar composition. Interface samples proved more difficult to extract. A detailed photographic and written record of interface properties was taken during sampling to improve the understanding of its characteristics. On transfer to the testing apparatus, the samples were oriented in the shear box cradle so that shear stresses would resemble those experienced in the field. Samples were loaded and subjected to shear stresses according to procedures described for drained and undrained direct shear tests in Head (1982). A description of testing procedures follows.

Conditions for peat testing, as far as possible, reflect field conditions immediately prior to failure. In all cited cases of peat mass movement (see Chapter 3, section 3.2.4), ground conditions are saturated due to high antecedent rainfall, with a water table, at, near or over the ground surface (Carling, 1986; Dykes and Kirk, 2001). Loading scenarios, based on an approximate saturated bulk density of 1 Mg m^{-3}, accommodate realistic loading weights, equivalent to peat depths for peat and interface shear tests, and peat and clay overburdens for substrate shear tests. For example, using a bulk density of peat of 1 g cm^3, load ranges of 4 kPa to 12 kPa for peat represent field saturated peat depths of between 0.4 and 1.2 m. These depths are consistent with the ranges of peat depths recorded at slide failures and discussed in Chapter 3. Higher loads for interface and substrate (up to 36 kPa) reflect the increased overburden and depth of material associated with incorporation of the deeper mineral layers.

Strain rate (the rate at which the stressed sediment undergoes deformation) may influence strength characteristics (Gibson and Henkel, 1954; Head, 1982). Therefore, realistic strain rates were chosen that would induce sufficient deformation to produce failure over time frames to the field. Two theories of deformation rate dominate the peat slide literature. The first suggests that deformation is long term and progressive. The duration of this 'creep-like' (Mitchell, 1938) process is unknown, and may represent a few millimetres over several hours to fractions of a millimetre over several months. The second theory suggests that failure is rapid (Hudleston, 1930; Carling, 1986; Dykes and Kirk, 2001), accompanying high strain over short periods. Again, there has been an absence of direct observation. Accounts relating peak recorded rainfall intensities and the known inundation of valley channels with deposit (e.g. Carling, 1986; Coxon *et al.*, 1989) suggest the time from onset of failure to delivery of runout debris is not more than thirty minutes. Hence, initiation and duration of shearing failure, triggered by peak rainfall, cannot exceed this period.

In experimental terms, the difference between rapid and progressive failure is reflected in the pore-water pressures generated during shearing. In engineering terminology (see Table 6.2), tests may be conducted under either drained or undrained conditions. Strain rates in drained tests permit pore-water to drain through structural readjustment of the tested material. Hence pore-water pressures do not increase in compression, reducing the particle-particle contact, and generating inappropriately low shear strength parameters (Vickers, 1983). Undrained tests use rapid strain rates to encourage the opposite, with pore-water confined, and pressures pushing the particles apart and reducing the frictional component (ϕ) to negligible values. In these tests, material strength is purely a function of the cohesive character (c) of the sediment (Head, 1982). However, even for fine particulate material such as clay, test results based on failure strains applied over periods greater than thirty minutes rarely induce true undrained conditions (Head, 1982).

Accordingly, a strain rate of 0.18 mm min^{-1} (10.8 mm h^{-1}) was used for the undrained condition. This allowed the maximum displacement of the two sample halves to occur in just under an hour. In practice, trial tests revealed that peak strengths were attained after only a few millimetres displacement, and hence in a period closer to, or under the thirty minutes previously specified. Under drained conditions, a much slower rate of 0.004 mm

min^{-1} (0.24 mm per hour) was utilised, leading to full displacement in just over 24 hours. Although probably not as slow as the hypothesised progressive creep mechanism, it is likely that deformation was able to proceed without a rise in pore-water pressures.

Peat samples were subject to undrained tests only, at loads consistent with a range of peat overburden depths. The practical constraints of the shear box cradle depth precluded the use of loads in excess of 12 kPa, as consolidation rates would have pushed the top plates into line with the shear plane and risked damage to the machine.

Interfaces rather than transitions were tested, as these represented the most pervasive peat substrate contact type in the materials brought back from the Hart Hope site. Interface samples were subject to undrained tests only, of which four were conducted. Given the likely variability in peat substrate contacts at the interface, it would have been preferable to perform more than the standard number of tests required for derivation of shear strength parameters in homogenous materials (3 - 4 tests; Head, 1982; Vickers, 1983; Craig, 1997). However, it was not possible to extract more than four samples for testing from the large sample tins, without disturbing the surrounding interface to the extent that pre-test fracturing had initiated. Figure 6.3 shows a range of interface types in one of the interface samples, with the location of sub-samples shown. The interface is highly variable in nature and extent. In order to maximise the value of the interface samples, a photographic log (from which the photograph in Figure 6.3 is taken) was recorded throughout the procedure of sub sampling. This log provided a qualitative account of the peat substrate contact and its response to gentle disturbance during sampling.

Owing to failure of the standard shear box apparatus mid-way through the test programme, the consolidation stage for one of the peat tests was lost, and all subsequent tests had to be continued on small shear box apparatus, for which consolidation stage logging was unavailable. Additionally, the minimum standard load that could be conducted across testing apparatus corresponded to 20 kPa, or 2.0 m equivalent peat overburden. The further implications of these circumstances are considered in section 6.3. An additional restraint on the testing programme was the availability of sample. Particularly heavy restrictions on countryside access in the North Pennine area throughout 2001 and into 2002 (due to Foot and Mouth) prevented the acquisition of further samples in the event that those already taken were sub-optimal.

Figure 6.3. Peat-clay interface types in sheared sample. Fractures are visible just above the peat-substrate contact, highlighted between points a) and b) and between points c) and d). Contact types are shown schematically to the right, and can be seen to varying extents throughout the sample.

Subsequent to shearing, samples were left to air dry for the calculation of volumetric moisture contents and dry bulk densities. They were then examined to ensure that larger organic and mineral elements had not influenced the formation of shear planes. Index property and geotechnical tests were carried out in order to aid in interpretation of shear strength results. These were as follows:

i) particle size analysis of sheared substrate samples to evaluate consistency of tested material;

ii) derivation of liquid and plastic limits for sheared clay samples;

iii) bulk property micro-profile of interface sample;

iv) shrinkage and swelling of peat and clay around interface.

For each sheared substrate sample, particle size was determined with replicated runs using a Coulter™ Laser Particle Granulometer. The procedure for this is described in Chapter 7.

Consistency limits were determined using 500 g of substrate sample, according to the procedures described in BS 1377. Liquid limits were determined using a cone penetrometer, considered more reliable than the alternative Cassagrande apparatus, and giving more reproducible results (Head, 1982; Vickers, 1983).

A micro-scale profile was carried out at 1 cm sampling intervals through the extent of the 8 cm peat substrate interface in one of the interface sample tins. Wet bulk density, weight moisture contents organic matter content were determined according to the procedures described previously.

6.2 Results

The description of results is divided into two main sections. The first considers site-wide stratigraphic units from the peat surface to substrate for all sites, and their arrangement and bulk properties. This provides a regional assessment of the variety of peat blanket and substrate materials in which peat slide failures occur. The second section considers the

Hart Hope case study, both in terms of this wider context, and with respect to micro-scale geotechnical criteria for slope stability. Bulk property data involved in both approaches links the regional, site and micro-scale assessments of material.

6.2.1 Stratigraphic assessments of peat and substrate characteristics

Stratigraphic unit properties were determined through classification schemes for both long profiles and for the head scar samples. At most sites, core sampling was straightforward, although Coldcleugh Head could not be sampled due to access restrictions. Deeper peats (such as at Benty Hill and Dow Crag) exhibited considerable suction at depth, while wood layers proved difficult to penetrate at Dow Crag. At a number of sites, it was not possible to bring substrate up in the Russian corer, as the 10 cm core head was unable to penetrate either stiff substrate material or basal stone layers. It is assumed in these cases that the peat-substrate contact was within 10 cm of the lowest returned sample depth. At a number of sites (most notably Nein Head 2), the corer penetrated the substrate to a full chamber depth (0.5 m), suggesting extremely soft substrate material.

For the remainder of this chapter, unless specific material properties are being referred to, the four-fold descriptive definition of Akroyd (1964) will be used to contextualise discussion of peat properties. Akroyd recognised peat as distinct from mineral soils, and defined a simple structurally based framework for the description of peat deposits. Peat is referred to as fibrous, pseudo-fibrous, amorphous or intermediate according to its structural composition (Table 6.3). This is a simple but effective summary of peat type, and provides a clearer basis for description than the many variants of classification proposed in the International Peat Congress' Proceedings series (1968, 1972, 1980). Mineral substrate characteristics will be referred to in the context of soil texture, i.e. relative proportions by weight of clay, silt and sand sized particles (Rowell, 1994).

6.2.1.1 Stratigraphic units in cores from the scar margins

The layer properties of each core were plotted in TiliaGraph^{TM} and zoned using constrained cluster analysis in CONISS^{TM}. Stratigraphies were plotted along scar-adjacent slope profiles, with the location of the major and minor boundaries determined by cluster analysis. An example is shown in Figure 6.4. Additionally, a fibre index was calculated

Table 6.3. Four-fold descriptive framework for peat classification (after Akroyd, 1964)

		Troels-Smith Characteristics				Von Post Characteristics				
Peat class	Description	Sediment classes	Darkness range	Wetness range	Stratification	'H' range	'C' range	'F' range	'W' range	Plasticity
Fibrous	firm, moderately tough and non-plastic, shows original slightly decayed plant structure	Th: 2-4 Tb: 2-3 Sh: 1-2	Nig: 2-3	Sicc: 0-4	Strf: 1-3	2-5	1-3	1-3	0-1	n/a
Pseudo-fibrous	fibrous in appearance, but soft, non-coherent and plastic; fibres visible in freshly broken surfaces but destroyed on remoulding; readily extruded as paste	Th: 1-2 Sh: 3-4	Nig: 3-4	Sicc: 2-4	Strf: 0-1	5-8	0-1	0-2	0-1	yes
Amorphous	original plant structure completely destroyed, composed of fine grains in plastic mass; organic counterpart to clay	Th: 2-4 Tb: 2-3; Sh: 1-2	Nig: 4	Sicc: 1-3	Strf: 0-1	9-10	0	0	0-3	yes
Intermediate	mixtures of more resistant elements among more strongly altered matrix; mixtures of amorphous and inwashed minerogenic	Th: 1-2 Sh: 1-3 As: 2-3 Gmin: 1+	Nig: 1-3	Sicc: 0-4	Strf: 3-4	6-10	0-1	0-1	0-2	yes

Notes

Descriptions based upon Akroyd (1964), Troels-Smith and von Post ranges based upon descriptions in original schemes.

As	Argilla steatodes	Clay <0.002mm
Gmin	Grana minora	Fine, medium and coarse sand (0.06-2.0mm)
Sh	Substantia humosa	Humified organics beyond identification
Th	Turfa herbacea	Roots, stems and rhizomes of herbaceous plants
Tb	Turfa bryophytica	The protonema, rhizods, stems, leaves etc. of mosses

Figure 6.4. Dow Crag, scar adjacent core slope profile. Depths shown at half metre intervals for each core.

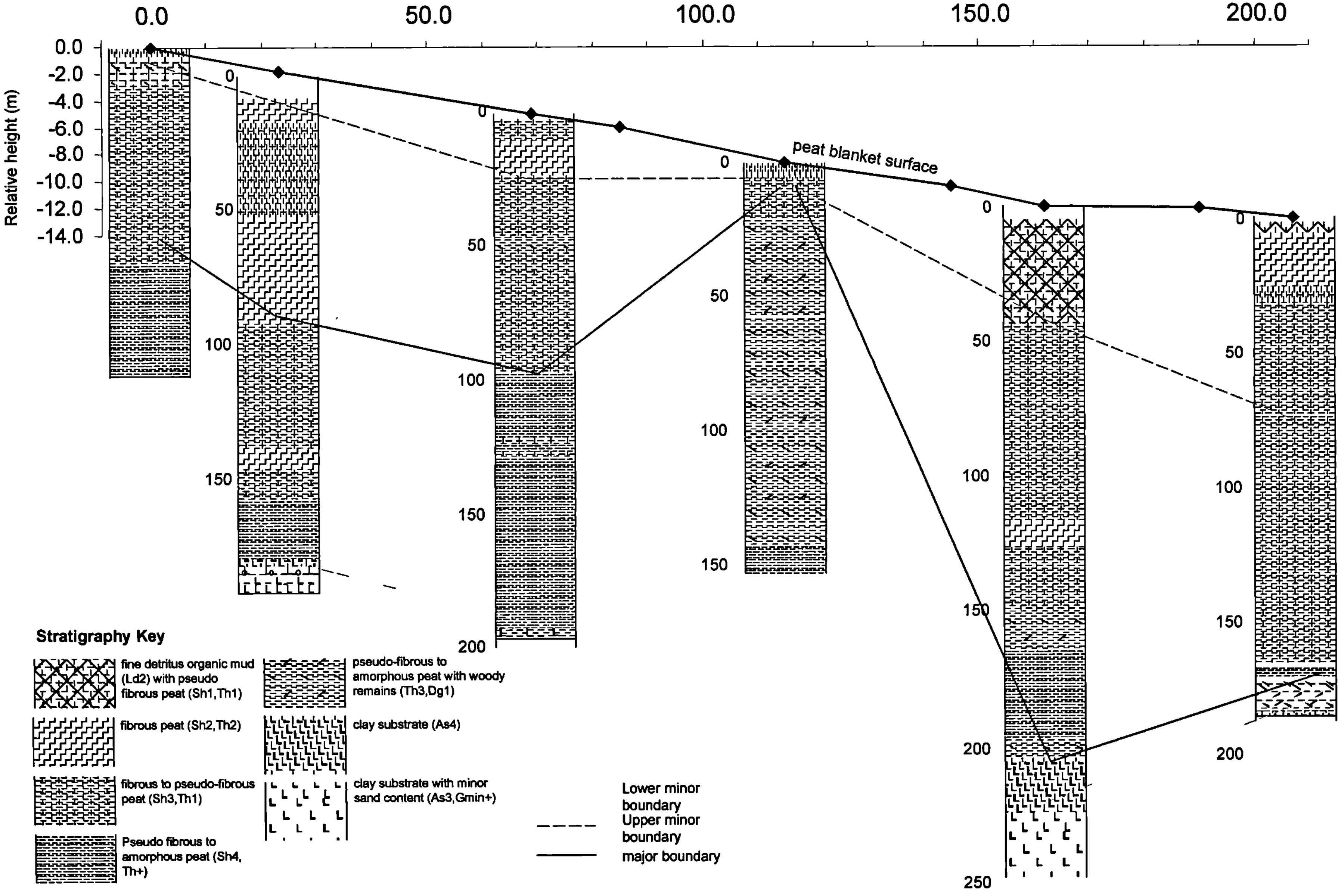
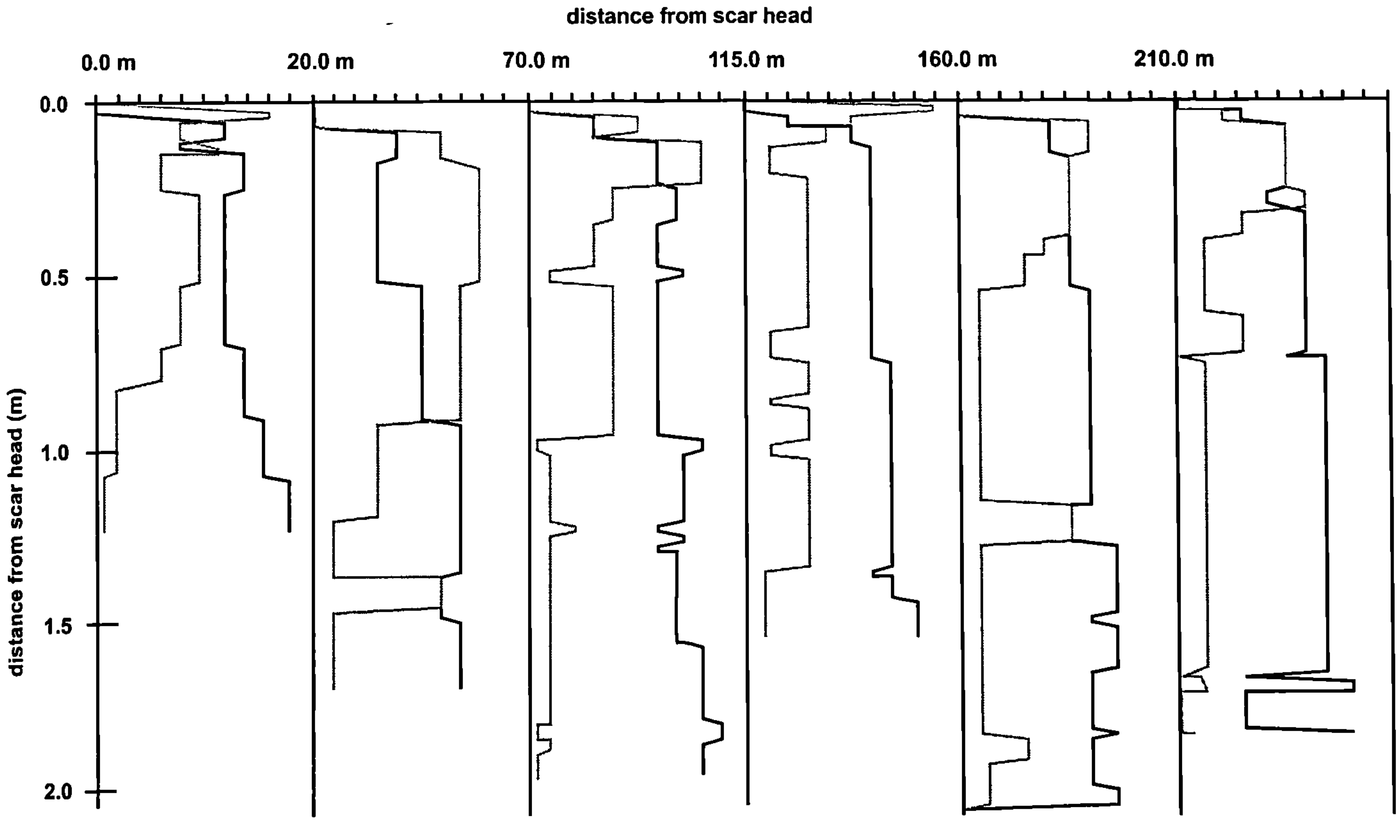
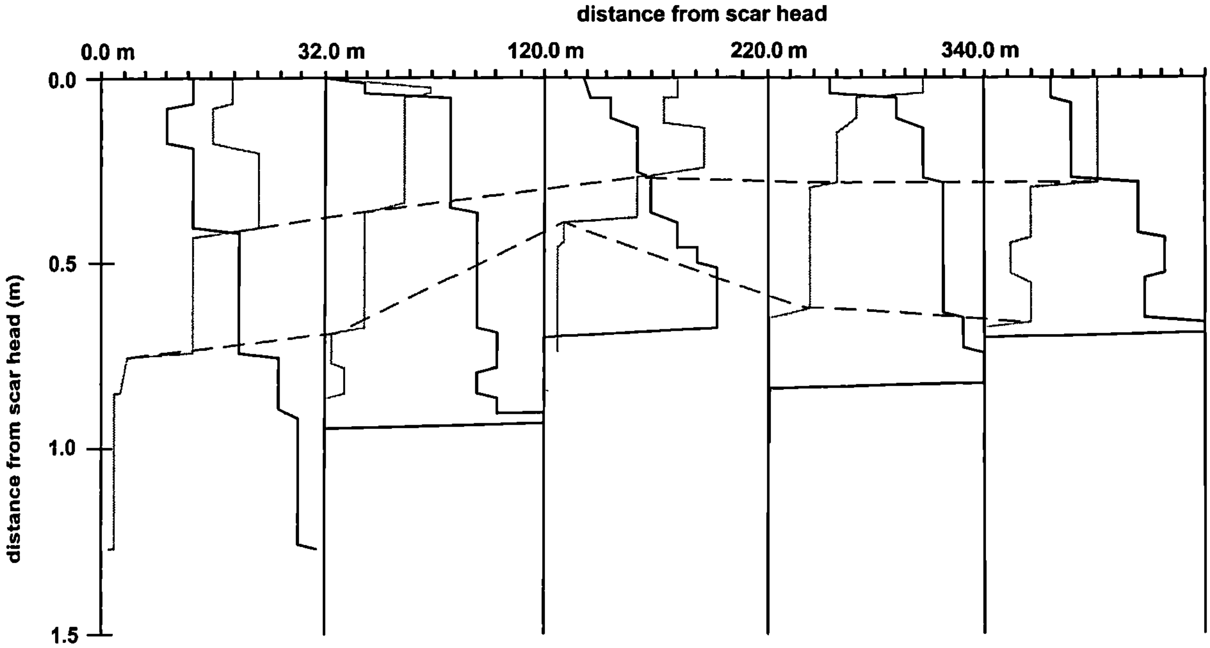


Figure 6.5. Fibre index and humification plots for core long profiles at Dow Crag (1930) and Nein Head 2 (1983)

a) Dow Crag: fibre profile is not distinct between cores



b) Nein Head 2: fibre profile allows layer discontinuities to be discriminated (hashed lines)



—— von Post humification

—— fibre index

– – layer discontinuity

NB: all scales are 1-10 between cores, distances from scar heads are indicative only from the relative proportions of fine and coarse fibres in each layer, and plotted against humification for each core. Cores were then ordered according to slope position and plotted in a fibre/humification index chart, examples of which are shown in Figure 6.5. The fibre index is based upon the relative significance of fibre types in the provision of tensile strength. Fine fibres are recorded where fibre diameters are less than 0.5 mm, while coarse fibres are in excess of 0.5 mm. Hence, individually, coarse fibres are likely to be of greater tensile strength than fine fibres. The proportion of fine fibres (0 - 3 by the von Post scheme) was added to the proportion of coarse fibres (0 - 3), the latter doubled to represent its greater tensile significance. This is not a quantitative representation of fibre strength, rather a measure of relative changes in fibre content significance with depth. It should be noted that humification and fibre content are inversely related in the classification, and hence variations within each core (Figure 6.5) are interdependent.

The hydrologically active acrotelmic layer comprises a thin surface covering (< 5 cm) of strongly fibrous material (Th_{2-3}) overlying wetter and partially decayed plant matter (Th_2, Sh_2), the latter extending to between 10 and 25 cm of the upper core depths. Only at the two Meldon Hill sites and Middlehope were significant rootless mossy layers (Tb_2) found at the peat surface.

Immediately beneath this layer, marking the beginning of the catotelm, was found a more humified peat (Sh_3, Th_1), with fibres still exhibiting some tensile strength. This layer could extend for up to half of the total core depth (0.25 – 0.50 m) in many cases, although it was largely absent at some sites (e.g. Benty Hill, Langdon Head). The lower peat layers in most profiles correspond to the pseudo-fibrous (H_{8-9}) and amorphous (H_{10}) categories of Akroyd, although these are not separated in the stratigraphy profiles in Figure 6.5. The lithology plotting module of TiliaGraph cannot distinguish minor (+) components, while the distinction between amorphous and pseudo-fibrous peat is also below the lowest 'presence' threshold of the plots. Truly amorphous peat (H_{10}), with no fibre remnants is only found adjacent to the upper scar of Feldon Burn, adjacent to the lower scar of Iron Band, and in very thin layers (< 5 cm) at the bases of some of the other failures (e.g. Meldon Hill East and West, Nein Head's 2 and 3 and Hart Hope).

Peat depths vary considerably adjacent to the scar areas of each failure. Figure 6.6 shows peat depth ranges for each site, with the upper and lower cores highlighted in each case. In the Noon Hill area peat depths range between 0.75 and 1.50 m for the two adjacent Nein Head failures, both terminating within the peat blanket. At the nearby Hart Hope and

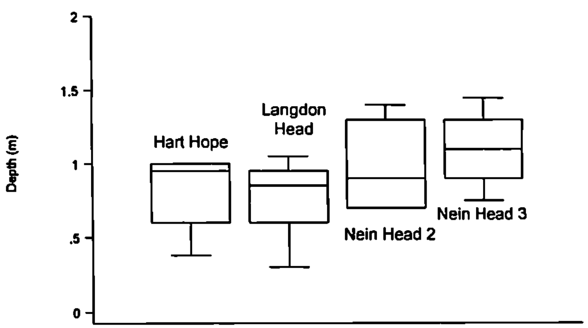
Langdon Head failures, peat depths are lower with a maximum of around 1.0 m in the upper parts of each failure, with depths thinning to 0.25 m as the slide scars extend beyond the blanket peat limits. Peat depths are similarly low at the two Meldon Hill failures, ranging between 0.20 and 1.20 m. The deeper peats of the Stainmore plateau give an elevated range of between 1.20 and 2.00 m at Dow Crag and 0.50 and 1.50 at Iron Band. Benty Hill and Feldon Burn range between 0.40 and 1.50 m, and are situated mid blanket, whilst peat depths are shallow at the marginal Middlehope (0.20 to 0.75 m). Within the gentle relief spanning the core sequences, morphometry appears to play little part in determining local peat depths. Peat depth maxima and minima are unrelated to concavity or convexity. Only proximity to the blanket margin in the lower scars of some failures appears to play a clear role in reducing peat depths downslope.

Many of the sites exhibited signs of past disturbance during peat formation through inwashed mineral layers. Feldon Burn displayed localised inwash at 150 m down slope, while a prominent double clay layer was found adjacent to the upper scar at Middlehope. Much of the peat profile at Meldon Hill East exhibits a moderate clay component (As_1) after 60 m down slope, while the lower scars of Langdon Head and Benty Hill also show the presence of clay. The whole of the West Grain core sequence was typified by extensive peat/mineral mixes, with local highly clayey and highly humified layers. Coring proved a particularly strenuous activity at this site, and no clear As_4 substrate could be brought to the surface before a depth at which coring became impossible (1.3 m).

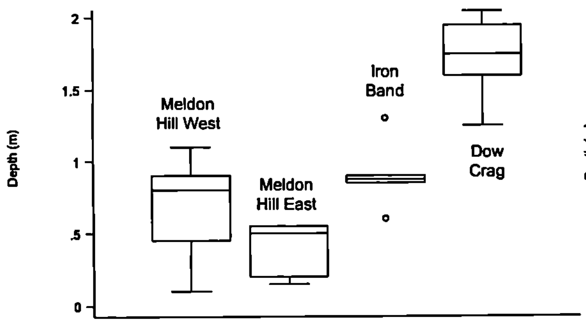
The substrates at most sites appeared clay-like in nature ($As_{3\text{-}4}$), with a soft, plastic feel. Slight grittiness indicated localised fine sand ($Gmin_+$), usually present in inwashed layers or around small weathered clasts. At the base of Dow Crag, Meldon Hill West and adjacent to the upper scar at Hart Hope, significant quantities of sand were found ($Gmin_1$). At many sites, the substrate was soft enough, despite its clay content, for considerable depths of material to be brought to the surface (20 cm at Iron Band, Middlehope, Hart Hope and Langdon Head; 30 cm at Feldon Burn and Meldon Hill East; 60 cm at Meldon Hill West).

In general, humification increased with depth and declining fibre content, after a sharp rise in the uppermost part of each core (Figure 6.7a and c). Correspondingly, fibre index was greatest in the upper few centimetres of each core, dropping rapidly thereafter (Figure 6.7b and d). A number of profiles exhibited localised highly fibrous layers at depth (e.g. West Grain), some of which were traceable at consistent core depths for up to 100 m of slope

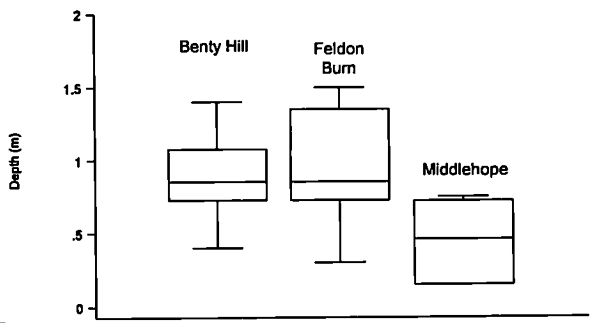
Figure 6.6. Core peat depth ranges for all cored sites (excluding West Grain)



a) box plots of peat depths for Ireshope Burn failures



b) box plots of peat depths for Stainmore and Meldon Hill failures



c) box plots of peat depths for isolated failures

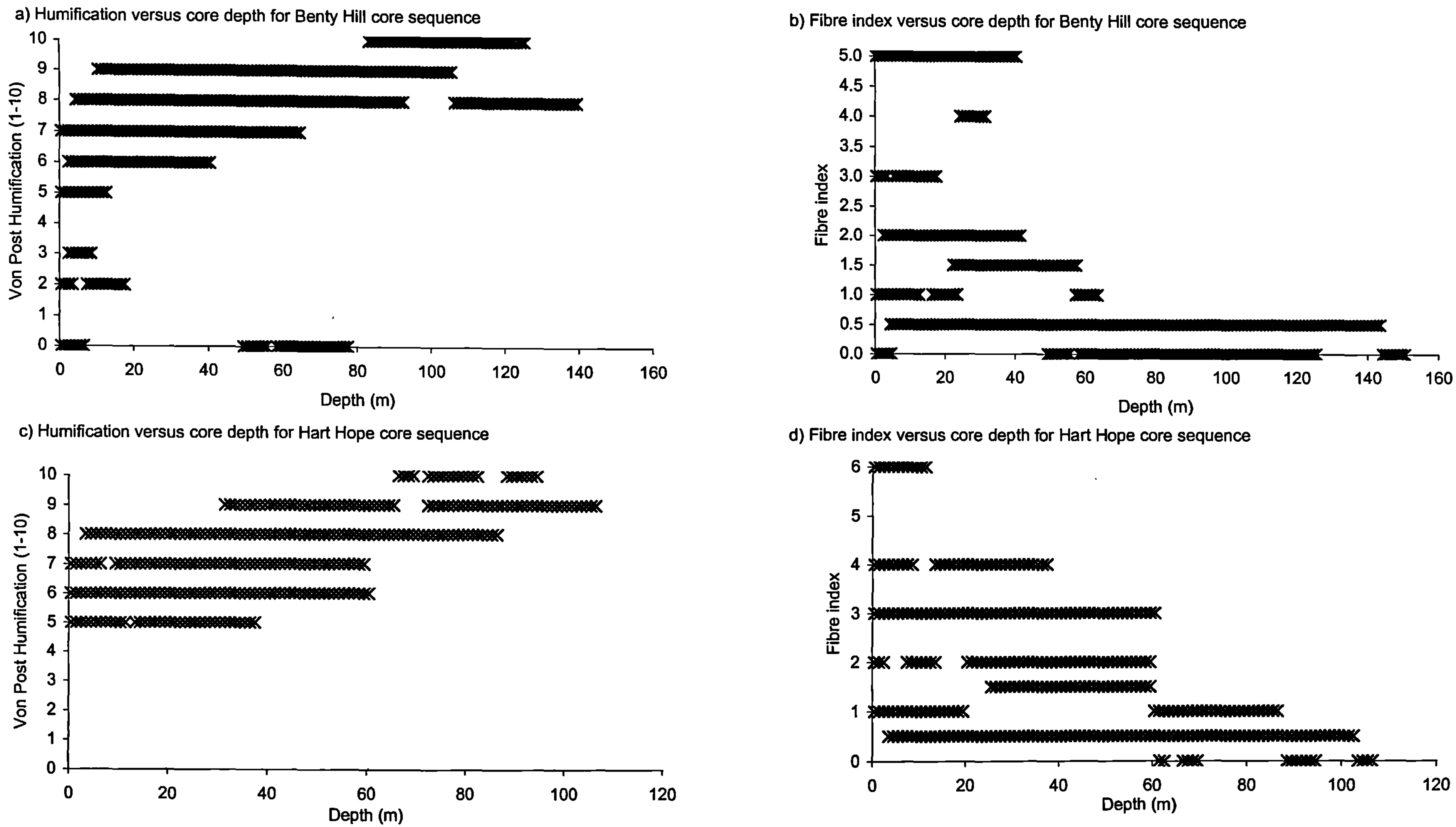


Figure 6.7. Humification and fibre index plots for Benty Hill and Hart Hope, illustrating interdependency between fibre content and humification with depth

distance (e.g. Dow Crag). Some core sequences (e.g. Nein Head 2; Figure 6.6b) exhibited a second major fall in fibre content from a fibre index of 4-6 to 0-2 at approximately half the depth of each core, with fibres identified in the cores disintegrating on remoulding. The consistent fibre layers traceable along core sequences confirm the likelihood of past, spatially consistent surface vegetation communities.

Although fibre contents relate to depth (Figure 6.7), there appears to be little spatial control over fibre content or humification at most of the failures. Fibre-index/depth relationships showed consistency over 10's to 100's of metres of slope distance (Hart Hope; Figure 6.6c). Scar adjacent areas were not obvious by lower fibre contents and higher humification, nor did peat corresponding to undisturbed locations exhibit higher fibre contents and a more consistent matrix.

At three sites, fibre indices showed anomalies, and were high (greater than 5) through at least half of the profile depth and for some distance downslope. This was the case at Nein Head 2, Nein Head 3 and at Dow Crag. Both of the former failures have already been noted as being strongly rafted over their scar areas. The morphology of Dow Crag has been obscured by its age, but rafting is noted in both its upper and secondary scar (see Chapter 4). Although Langdon Head, West Grain and Benty Hill also exhibited significant rafting, fibre indices were generally low (less than 2) throughout most of the core depths. Only surface fibres associated with the acrotelm were present.

The zones of peat-substrate contact within each core were defined as either transitions or interfaces (see Figure 6.3). Interfaces, in which a sharp contact was visible between peat and substrate, were most prominent at Nein Head 2 and Feldon Burn. Transitions dominated at Nein Head 3, Middlehope, Langdon Head and Benty Hill. Turbulent contact zones, in which neither an interface nor transition is clear, dominate at Dow Crag, Iron Band, Meldon Hill East, Meldon Hill West, Hart Hope and West Grain. The strength of these and other discontinuities in the profiles were quantitatively assessed using constrained cluster analysis.

The major boundaries, representing the major split in material type on the basis of physical properties alone, are plotted on Figure 6.8a against the depth of peat-substrate contact for each core. Each core is represented by one data point, separated by whether humification or another physical property is the main criteria for boundary definition. Values falling above the 1:1 line exhibit their major material boundary below the peat-substrate interface, and values below the opposite. Values on the line show the major boundary at the interface, and unsurprisingly represent a majority of the cores. The fact that humification is the major discriminator even below the contact depth for some cores, suggests that in these cases, the peat substrate contact is diffuse and organic matter is still mixed with mineral particles at depth. This generally is only the case in shallow cores of less than 0.5 m in depth. These often exhibit a graded transition from peat to mineral substrate, rather than the more pronounced interfaces at depth.

The depth to the first noticeable and continuous presence of mineral particles is plotted in Figure 6.8b. This again illustrates that at depth, the peat substrate contact is clear, whilst nearer the surface, the contact may be turbulent and extensive. Figure 6.8c illustrates that the lower boundary is often found in close proximity to the peat substrate contact, and reflects the relatively limited depths of core returned from below the contact.

	Major boundary		Upper minor boundary		Lower minor boundary	
	Primary property (%)	Secondary property (%)	Primary property (%)	Secondary property (%)	Primary property (%)	Secondary property (%)
Humification	84.1	3.6	53.7	4.0	24.0	12.5
Fine fibres	1.2	35.7	7.5	22.0	0.0	10.0
Coarse fibres	1.2	14.3	6.0	16.0	8.0	5.0
Wood remains	0.0	14.3	3.0	4.0	4.0	2.5
Dryness	2.4	3.6	4.5	12.0	12.0	7.5
Elasticity	2.4	17.9	1.5	16.0	22.0	35.0
Plasticity	0.0	0.0	1.5	14.0	4.0	12.5
Stratification	8.5	10.7	22.4	12.0	26.0	15.0

Table 6.4. Physical properties determining location of major, and upper and lower boundaries

Table 6.4 suggests that the upper minor boundaries are normally determined primarily by humification (53.7%) or by stratification (22.4%). In the former case, this is likely to be a product of the acrotelm/catotelm transition. In the latter cases, upper profile discontinuities result from localised disturbed layers, resulting in peat with visible (if perhaps physically unimportant) inwashed sediments or locally strong fibre mats (coarse and fine fibres together representing 40% of the secondary variable explanation). In the lower boundaries, the absence of fibres consequent on increased humification mean that mechanical properties such as plasticity, elasticity and dryness are the primary determinants of layer discontinuities, together explaining 60% of groupings.

Figure 6.8. Major and minor boundary associations for long profile core sequences

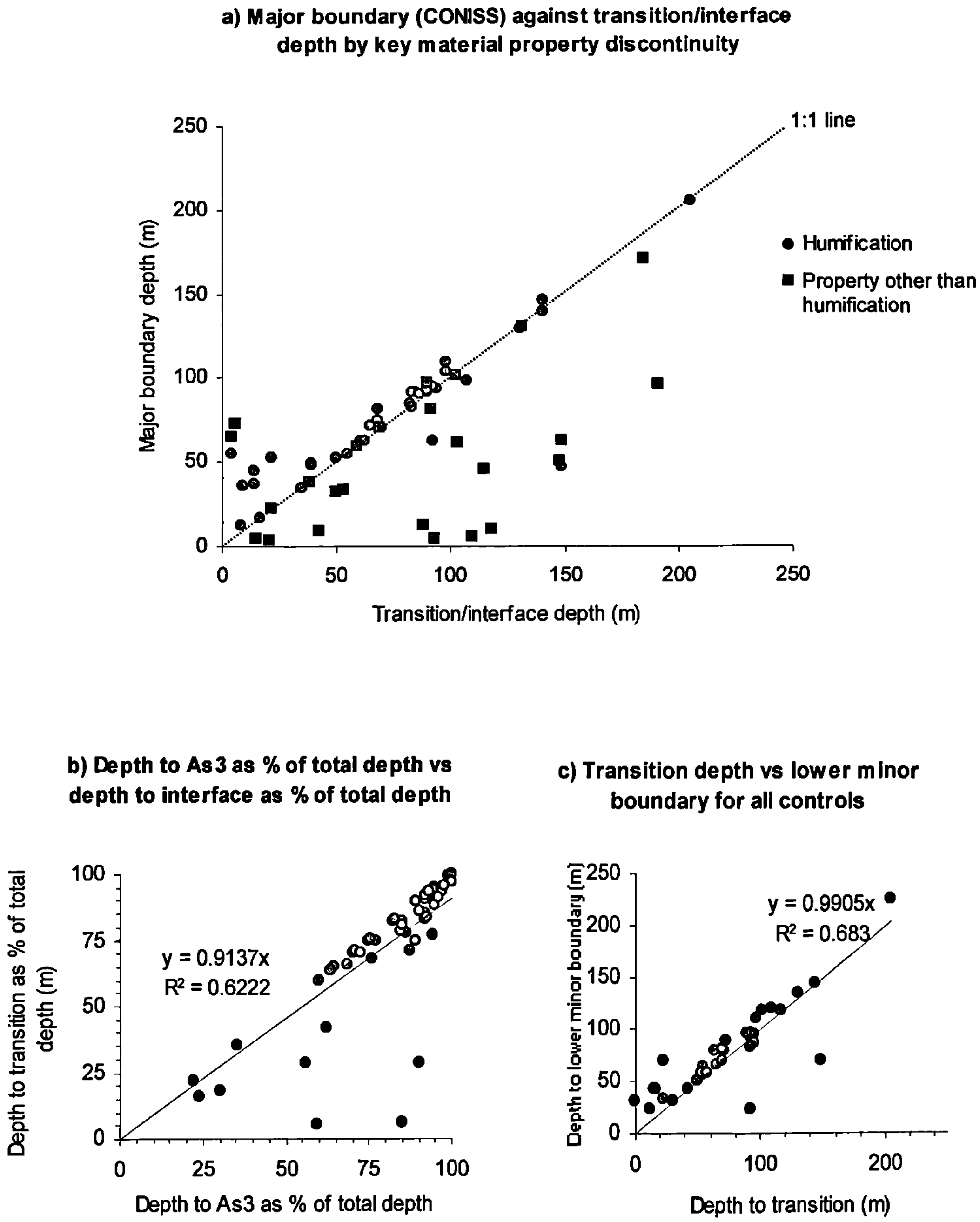


Figure 6.9. Scatterplot of wet bulk density against dry bulk density, separated by layer type.

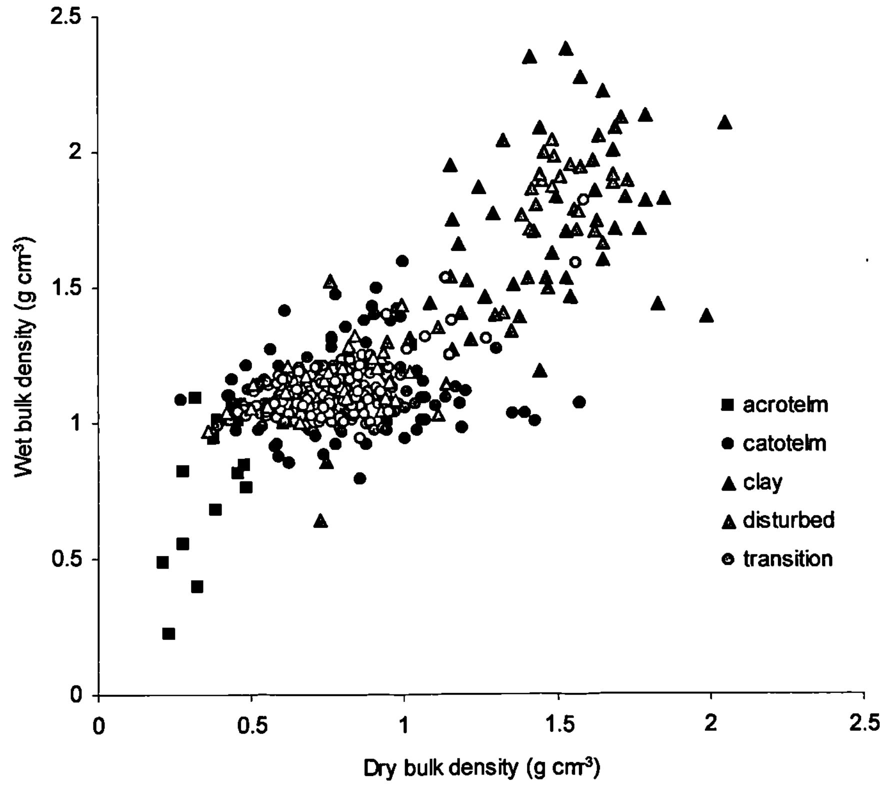


Figure 6.10. Scatterplot of volumetric moisture content against gravimetric moisture content, separated by layer type.

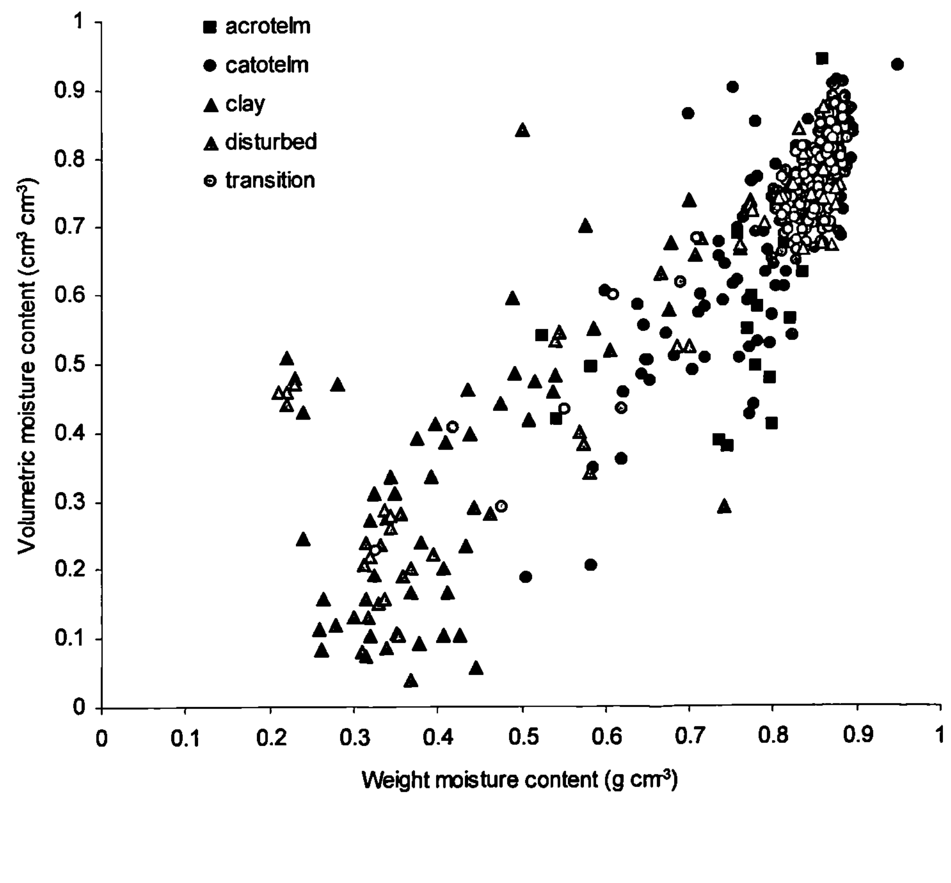


Figure 6.11. Scatterplot of dry bulk density against loss on ignition, separated by layer type.

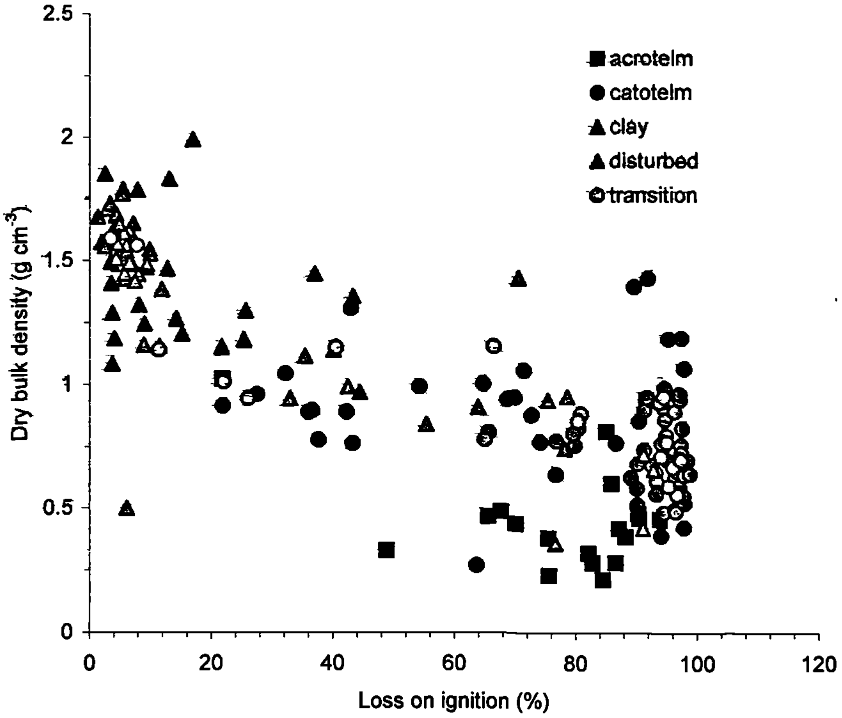


Table 6.5 Hydrological pathways at head scar exposures used for sampling.

Pathway Type	Sites at which present	Depths (m) below ground surface	Dimensions	Pipes at peat-peat transition	Pipes at peat-substrate transition	Pipes within substrate
Pipe	Nein Head 3	0.3 to 0.5 m	0.01 to 0.04 m diameter	yes	yes	
	Nein Head 2	1.3 m	0.14 diameter		yes	
	Meldon Hill West	0.15 to 0.5 m	0.01 to 0.03 m diameter	yes	yes	
	West Grain	0.7 m	0.06 m diameter		yes	
Point seepage	Meldon Hill East	0.05 to 0.6 m	0.15 m wide	yes		yes
	Middlehope	0.65 m	0.20 m wide			
Diffuse seepage	Nein Head 3	0.1 to 0.6 m	0.5 - 1.0 m wide	yes		
	Nein Head 2	0 to 1.0 m	0.5 m wide	yes		
	Meldon Hill East	0.10 m	0.5 m wide	yes		
	Hart Hope	1.1 m	1.5 m and 0.5 m wide		yes	
	Langdon Head	1.0 m	full extent of face (3.0 m)			yes
	West Grain	0.2 m	0.5 m wide	yes		

Table 6.6. Physical criteria (using von Post and Troels-Smith) used to distinguish acrotelm, catotelm, substrate, transition and disturbed material layers

	Troels-Smith Classification				Von Post Classification				
Layer	Class types	Darkness	Dryness	Elasticity	Humification	Fine fibres	Coarse fibres	Wood remains	Plasticity
Acrotelm	Th, Tb	2-3	0-4	0-1	0-5	2-3	2-3	-	no
Catotelm	Sh	3-4	2-4	0-1	5-10	0-2	0-2	0-2	yes
Transition	As, Sh	2-4	2-3	0-2	5-10	0-1	0	0-2	yes
Substrate	As, Gmin	1-3	3-4	2-3	-	-	-	-	yes
Disturbed	Sh, Gmin, As	2-4	2-3	2-3	5-10	0-2	0-1	0-2	yes

Table 6.7. Statistical summary of bulk properties for five major layers.

Layer	mean wet bulk density (g cm^{-3})	standard deviation	mean dry bulk density (g cm^{-3})	standard deviation	mean volumetric moisture content (cm^3 cm^{-3})	standard deviation	observations
Peat (acrotelm)	0.85	0.26	0.47	0.21	0.6	0.16	22
Peat (catotelm)	1.1	0.11	0.78	0.24	0.74	0.13	281
Disturbed	1.28	0.3	0.92	0.31	0.56	0.23	38
Transition	1.25	0.23	1.04	0.25	0.62	0.19	18
Substrate	1.71	0.32	1.83	1.62	0.34	0.21	79

continued...

Layer	mean gravimetric moisture content (wtot) (g cm^{-3})	standard deviation	mean gravimetric moisture content (w) (g cm^{-3})	standard deviation	mean loss on ignition (%)	standard deviation	observations
Peat (acrotelm)	0.76	0.1	3.85	1.68	77.57	17.5	22
Peat (catotelm)	0.82	0.07	5.54	1.89	83.29	20.49	281
Disturbed	0.69	0.18	3.46	2.21	44.79	32.49	38
Transition	0.7	0.17	3.45	2.17	48.21	33.14	18
Substrate	0.4	0.15	0.89	0.99	12.94	17.24	79

In some cases, where the substrate was not sampled, or because there are more significant discontinuities within the peat mass, major boundaries are located closer to the ground surface. This is the case at Nein Head 2, and in the upper slopes of Nein Head 3 and West Grain, where the major boundary falls between fibrous and pseudo-fibrous peat at approximately half the total peat depth in the upper 200 metres (slope distance) of the core sequence. All three failures are heavily rafted, and the significance of a major boundary within the peat is that the upper peat mass has distinctly differing properties to the lower stratigraphic units. Given that humification is the major determinant of the boundary position, this suggests high fibre contents in the surface layers.

6.2.1.2 Bulk properties in monoliths from the scar heads

The spatial arrangement of deposit layers at each slide scar head suggested some common stratigraphic unit characteristics between sites. Most profiles exhibited between three and five main peat horizons (or units), the uppermost of which were highly fibrous with occasional mosses, and were assumed to be acrotelm. Peat layers beneath this varied slightly in characteristics, but were generally well humified (H_{6-8}), saturated and greasy. The basal peats in all cases tended to be highly humified (H_{8-10}), with many exhibiting a pronounced woody layer.

The peat substrate transition varied between a sharp contact (e.g. Benty Hill, Hart Hope, Iron Band, Nein Head 3), through convoluted zones (e.g. Feldon Burn, West Grain) to gentle, graded transitions (e.g. Nein Head 2). Peat overlying many of the contact zones that appeared to be transitions, was seen to break cleanly away from the substrate with minimal application of force. This suggests that a visual basis for discriminating the nature of peat-substrate contacts may not reflect the true juxtaposition of the two materials. Comparison between the nature of interfaces across whole sites (section 6.2.1.1) and their scar heads reveal that interfaces and transitions vary at most sites from place to place, and that sites are rarely characterised by a single contact type.

The substrates themselves generally comprised two layers, the upper of which was a sandier, yellow grey clay, and the lower comprising a more homogenous soft grey clay. The boundary between the substrate layers varied between a strong horizon and more graded transitions. The material evidence for this is limited, with fibres generally absent, and both materials registering for plasticity and higher elasticity's (e_{2-3} when compared with e_{0-1} for peat). At its sandiest, the upper layer still registered only $Gmin_1$ in the Troels-Smith classification.

At most of the sites, signs of hydrological activity were noted. Point and diffuse seepage were present in both peat and substrate. Table 6.5 indicates hydrological pathways found at each site. Rounded pipes were found either at the transitions and boundaries between different layers of peat, between peat and substrate, or within the substrate itself. Similarly, diffuse seepage occurred along unit boundaries, with noticeably widespread peat-substrate interface drainage at Langdon Head and Hart Hope. Large zones of seepage spread throughout much of the peat face were noted at both Nein Head 2 and Nein Head 3, and at West Grain. Pipes varied in diameter between 0.01 m (at Nein Head 3) and 0.14 m diameter (at Nein Head 2), with a maximum of three pipes found in any one 3 m section. The material basis for their location is discussed shortly in the light of bulk property data for the monolith samples.

The monolith stratigraphies correspond well with the nearest cores. In the cases of Langdon Head and Dow Crag where rafting at the scar heads prevented sampling, local cores also closely resembled their respective monolith sets. This supports the use of monolith samples as broadly representative of the surrounding peats within the relatively limited altitudinal ranges of the peat slide sites.

Head scar bulk properties for each site were plotted in conjunction with their stratigraphic descriptions and von Post and Troels-Smith characteristics. On the basis of the criteria in Table 6.6, individual material samples were assigned to different layer classes. These classes corresponded to acrotelm and catotelm peat, substrate, transition material, and 'disturbed' as a general class for peat layers with significant (and usually irregular) mineral contacts not associated with a clear peat-substrate transition. The acrotelm was defined from the intact ground surface to the point at which fibre content became less than Th_2. Transition material was defined as the last material layer, 75% of which or less was organic, which directly overlaid continuous mineral sediment. The catotelm was defined as the continuous peat layer beneath the acrotelm and above the transition. Where this peat layer consisted of more than 25% mineral sediment (be it sand, silt or clay sized fraction), the layer was classed as disturbed. Graphical summaries of their ranges are shown in Figures 6.9 to 6.11, and statistical summaries of their values and interrelationships are shown in Table 6.7.

Figure 6.9 shows wet bulk density plotted against dry bulk density for all material types. When saturated, a majority of layer types have a bulk density in excess of 1 g cm^{-3}. The acrotelm samples are clearly the least dense, while the majority of catotelm samples (s.d.: 0.107) occupy the range 1.0 to 1.2 g cm^{-3}. Both transition and disturbed layers are similar in range, while the substrate layer is the most dense and variable (s.d.: 0.32). The distribution of layer types using dry bulk density was similar to that for wet bulk density, though with more pronounced disparity between peat layers and substrate. On this basis, the four fold descriptive definition of Akroyd (1964) appears physically sound. Disturbed and transition layers of potentially most interest vary between the catotelm-substrate limits, according to the extent to which they are organic or mineral in nature. Although each layer type occupies a clear range of densities, the relationship between dry and wet bulk density is generally poor within the discrete material classes (e.g. acrotelm r^2: 0.42; catotelm r^2: 0.01; substrate r^2: 0.15). Surprisingly, it is the disturbed and transition layers that show good correspondence between dry and wet bulk densities (disturbed r^2: 0.78; transition r^2: 0.75), suggesting a stability in material characteristics through a variety of moisture contents. The presence of wood in the catotelm peat, and stones in the substrate (both relatively independent of moisture related density changes) may partially explain the greater scatter in each class.

Moisture contents are plotted for all layer types in Figure 6.10. Both volumetric and gravimetric moisture contents provide a good basis for separation of material types, with acrotelm, catotelm and substrates clearly separated. Again transition and disturbed layers are separated from the substrate, with higher values falling within those for both peat types. Moisture content (w_{tot}: determined as a ratio of weight of water to total weight) and moisture content (w: determined as a ratio of weight of water to weight of dry matter) unsurprisingly show good correspondence (r^2: 0.67 - 0.86), but volumetric moisture content when compared with either weight-based measure shows less agreement (r^2: 0.37 - 0.93). Volume and weight based moisture contents correspond most closely in transition and disturbed layers, reinforcing the suggestion that peat-mineral layers are more stable layers in terms of bulk properties, despite the fact that there are a large range of organic-mineral mixtures present.

Loss on ignition values (Figure 6.11) are of less value in distinguishing layer types, with the almost exclusively organic acrotelm and catotelm occupying similar ranges (mostly from 75% - 98%), substrate (5% to 15%), but transition and disturbed materials spanning

Figure 6.12. Meldon Hill head scar stratigraphy and bulk properties

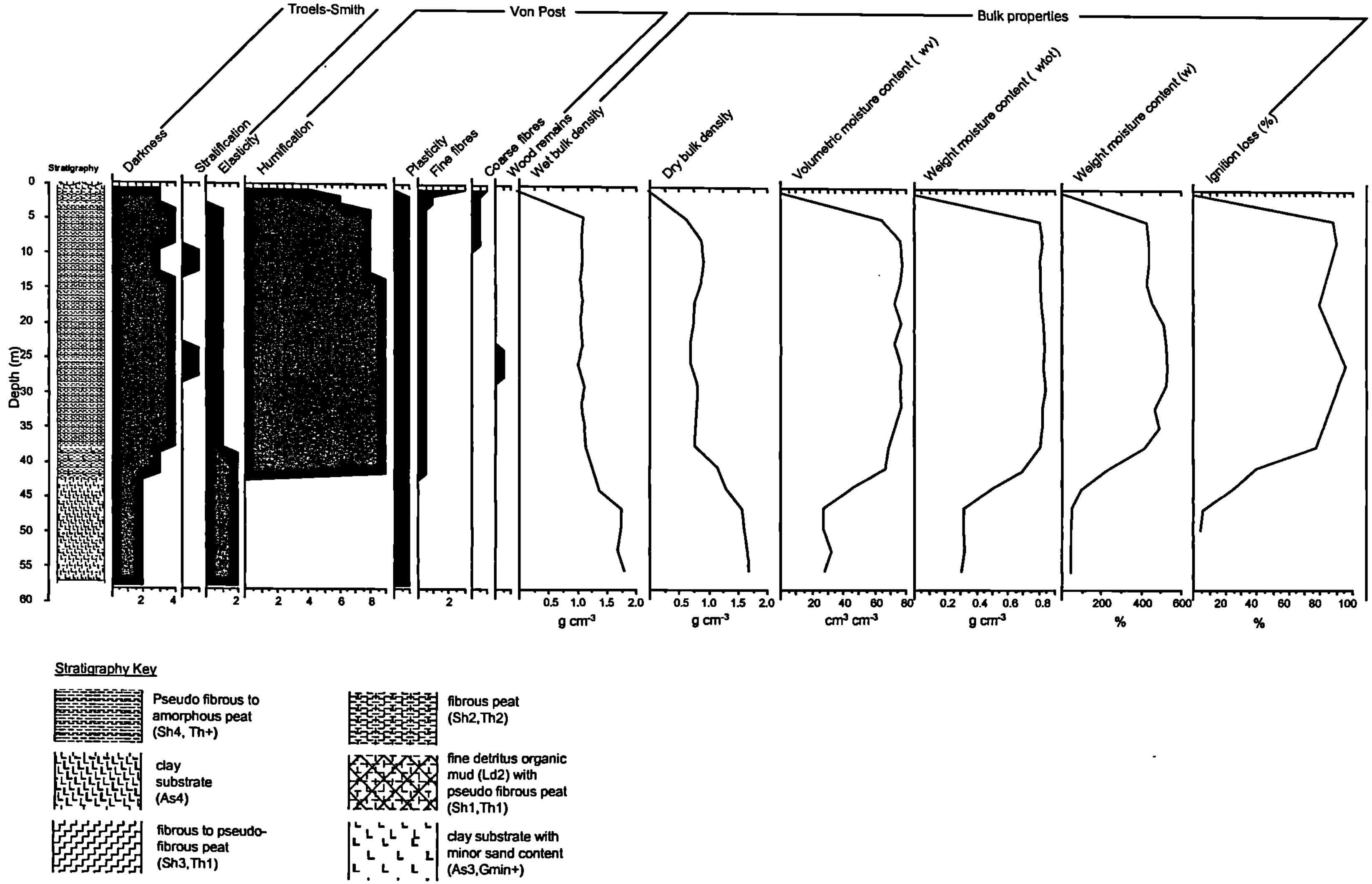


Figure 6.13. Benty Hill head scar stratigraphy and bulk properties.

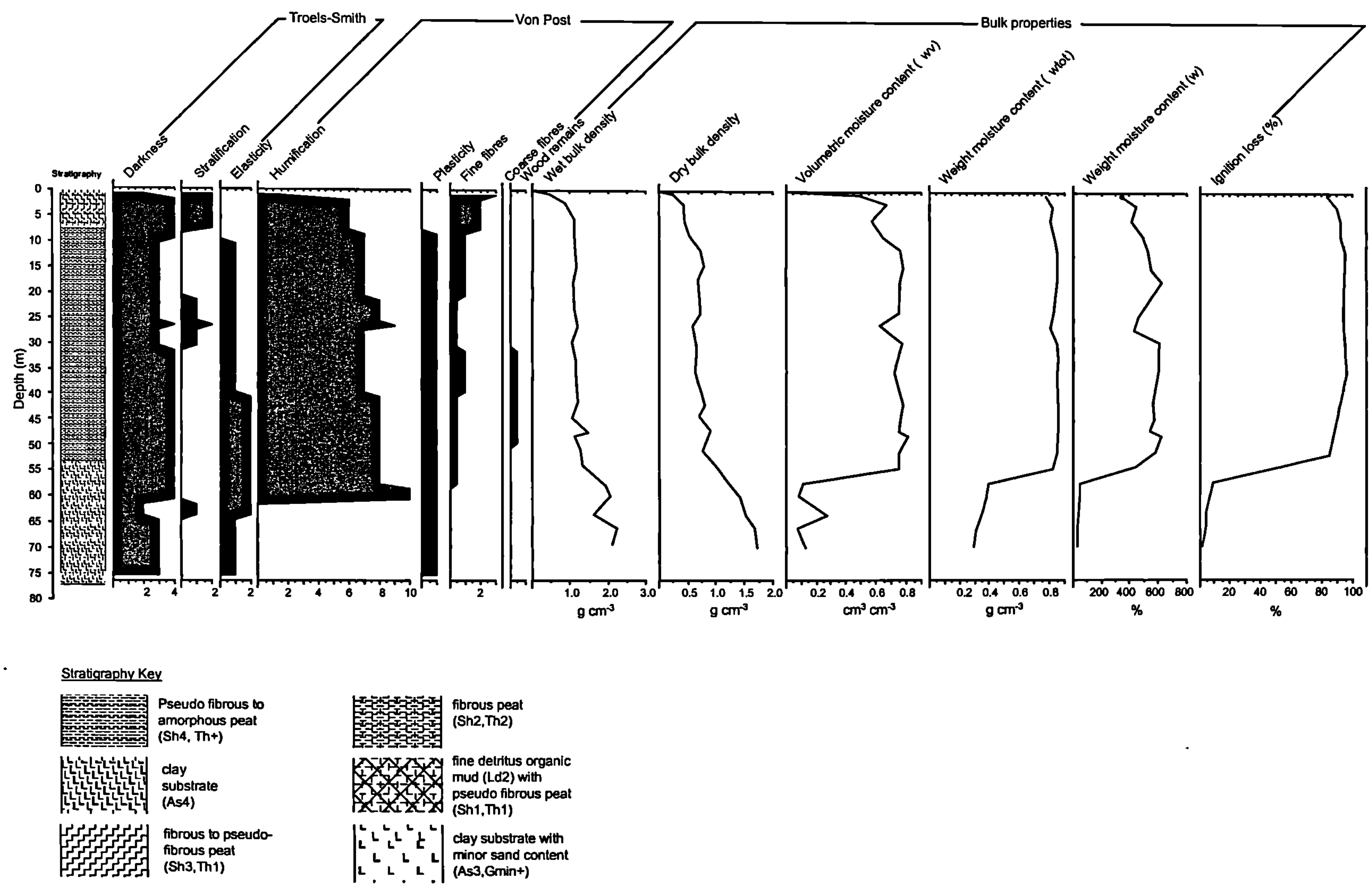


Figure 6.14. Nein Head 2 head scar stratigraphy and bulk properties

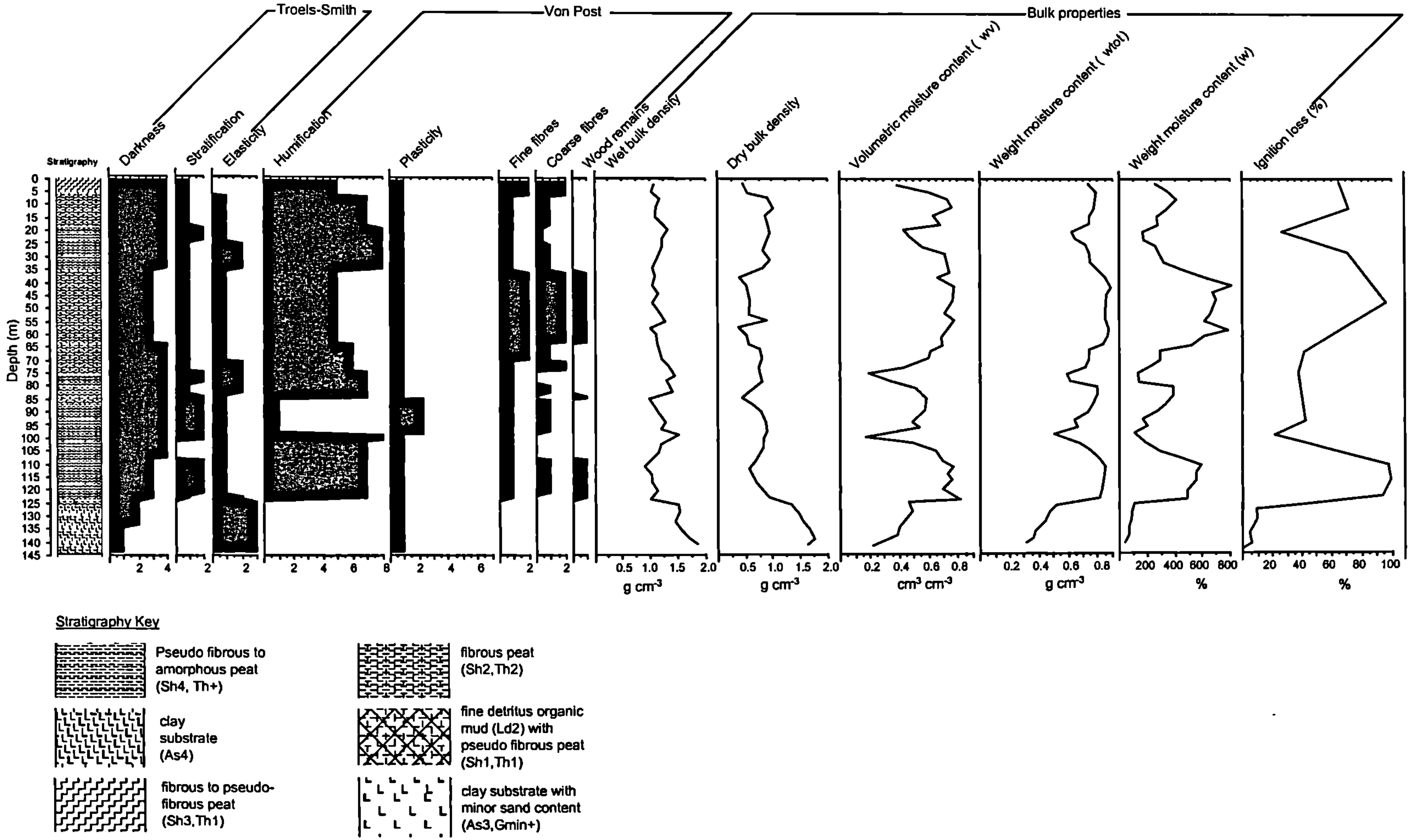
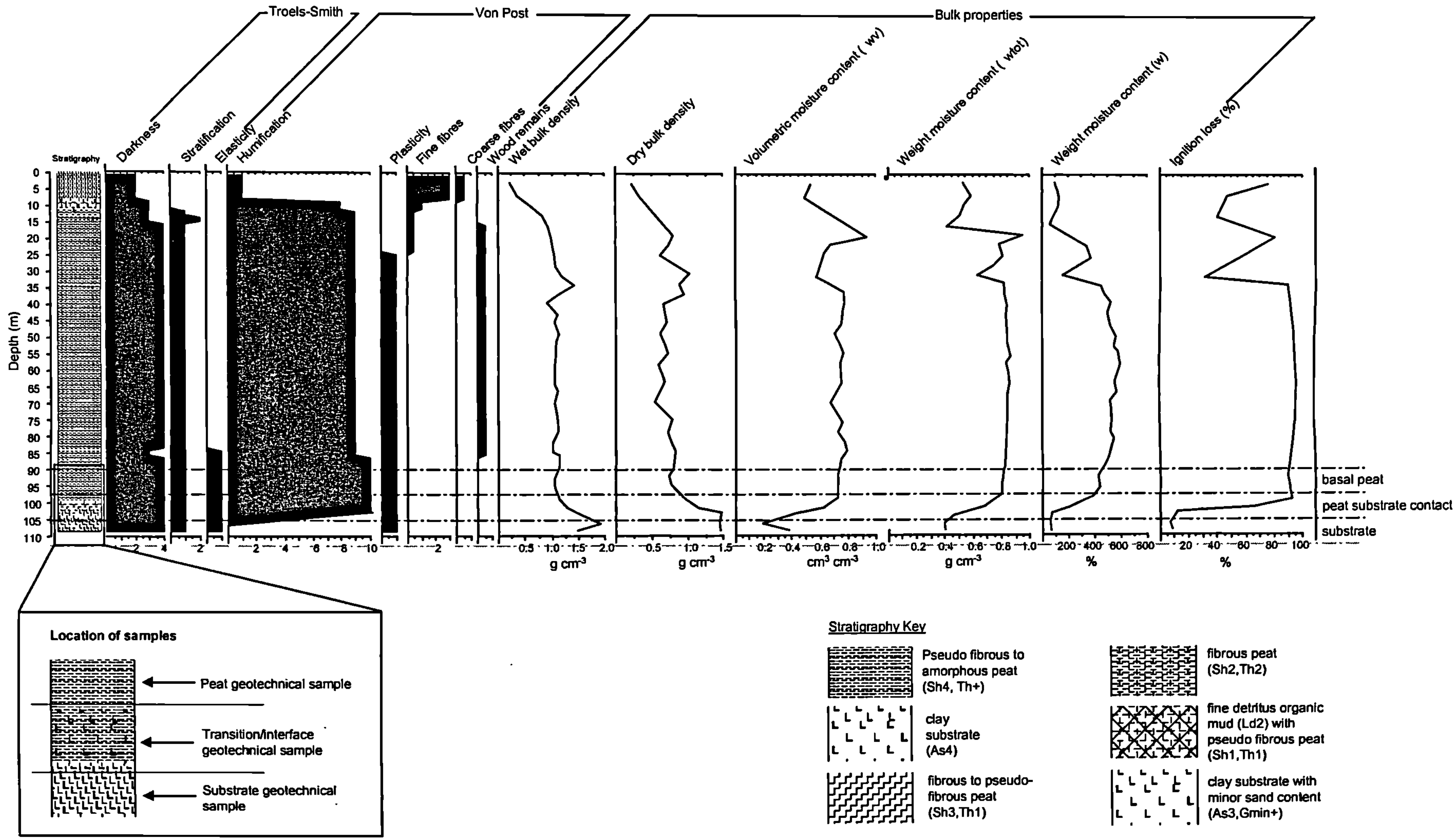


Figure 6.15. Hart Hope head scar stratigraphy and bulk properties, with relative locations of geotechnical samples shown. Note stability in ignition loss through highly humified catotelm.



the full range of organic matter contents. In general, loss on ignition values correspond poorly with other bulk properties (dry bulk density being the example in Figure 6.11), except in the substrate, where it is low (generally less than 40%) and corresponds well with weight measures of moisture content (r^2: 0.71 - 0.81), and in transition layers where it relates strongly to all other physical properties (r^2: 0.50 - 0.89) except dry bulk density.

The variation of bulk properties with depth is most clearly visible when plotted against stratigraphic and classification data. Four examples are shown in Figures 6.12 to 6.15, of Meldon Hill East, Benty Hill, Nein Head 2 and the Hart Hope case study site respectively. Dryness and boundary strength are not plotted within the Troels-Smith categories as they are represented by the moisture content values and visible gradations. At Meldon Hill and Benty Hill, the stratigraphic columns illustrate a graded transition in the former (Figure 6.12), and an interface in the latter (Figure 6.13). The changes from high loss on ignition values, moisture contents and from low to high bulk density are more rapid in Benty Hill as a result. Both plots illustrate relatively stable bulk properties and von Post/Troels-Smith criteria throughout their depths. This contrasts with Nein Head 2, in which the stratigraphy is complex, and bulk properties highly variable throughout the peat depth (Figure 6.14). This variability relates to fibre content, wood layers and inwashed mineral layers described in the von Post and Troels-Smith classifications. At Hart Hope, bulk properties again are stable with depth, except for the presence of a thin inwashed mineral layer in the upper profile (Figure 6.15). Humification reaches a maximum value of 10 in the bottom fifteen centimetres before grading over 5 cm into the mineral substrate.

The clear discontinuity in physical properties between overlying peat and substrate is visible in all four examples. Moisture content falls and bulk density rises through transition from peat to substrate. Generally, moisture contents and bulk densities are low in the upper 0-10 cm, corresponding with the highly fibrous and hydrologically active acrotelm. Occasionally, moisture contents are high (e.g. Figure 6.13), which may relate to surface saturation at the time of sampling, or to the presence of bog mosses in the upper few centimetres of the profile.

Of all the bulk properties, loss on ignition and weight moisture content (w_{tot}) are seen to be the most stable with depth (Figure 6.13), whilst volumetric moisture content and dry bulk density fluctuate the most. Variations in bulk properties relate most clearly to changes in the humification value, which is the material property with the largest semi-quantitative range (H_{0-10}) and hence the most sensitive to changes in stratigraphy. Increases in fibre quantity and the local presence of woody layers at Nein Head 2, West Grain and in the lower profile of Dow Crag (found throughout the rest of the scar profile) correspond to lower bulk densities in each case. Equally, the presence of mineral sediments within the peat profile increases bulk densities and reduces moisture contents. Highly disturbed profiles (such as Coldcleugh Head) show no consistent relationships between bulk properties and depth.

Interestingly, the initial changes in bulk properties associated with the peat substrate contact often pre-empt the defined contact positions determined using the von Post and Troels-Smith systems (e.g. Figure 6.12, at 30 cm). The rise in bulk density prior to the peat-substrate contact continues into the substrate at many sites (e.g. Figures 6.13, 6.14). Where significant quantities of the underlying substrate were extracted, some of the bulk density profiles indicate a positive relationship between wet bulk density and depth (e.g. Benty Hill, Feldon Burn, Nein Head 2, Meldon Hill East: r^2 : 0.56 - 0.76). This suggests that while bulk density does not increase as a function of depth within the peat mass, it may increase within the substrate as a function of loading by the peat mass. Loadings employed in the shear tests described shortly account for changes in the bulk density equivalent to 5% with 0.4 m of simulated peat overburden, and up to 20% with 1.2 m of simulated peat overburden. Hence, it is possible that the significance of peat overburden lies in its control of rapidity of spatial change in bulk properties in the substrate. This is speculative within the existing dataset, and samples to further depth would be required to test this suggestion.

Hydrological features may be related to local material characteristics. Pipes were found most prominently at Nein Head 3, occurring at 0.3 m at the transition between amorphous peat (H_{10}) and underlying pseudo-fibrous peat (H_8), and within a thin layer of transition material immediately overlying the substrate. At Nein Head 2, a single pipe was found within a similar transition layer at 1.2 m depth, while at West Grain a pipe occurred at the base of pseudo-fibrous peat overlying the substrate. Two pipes were present at Meldon Hill West, the upper (0.15 m depth) at the transition between pseudo-fibrous peat (H_8) and underlying transition peat (H_{10}), with a second within the substrate. Similarly, at the neighbouring Meldon Hill East, point seepage was present within the substrate material, and at the interface between fibrous and pseudo-fibrous peat. Point seepage was also present within a turbulent horizon of clayey-peat transition material overlying the substrate at Middlehope. Extensive diffuse seepage was found at Nein Head 2, Nein Head 3 and West Grain, though not in association with any specific layer type.

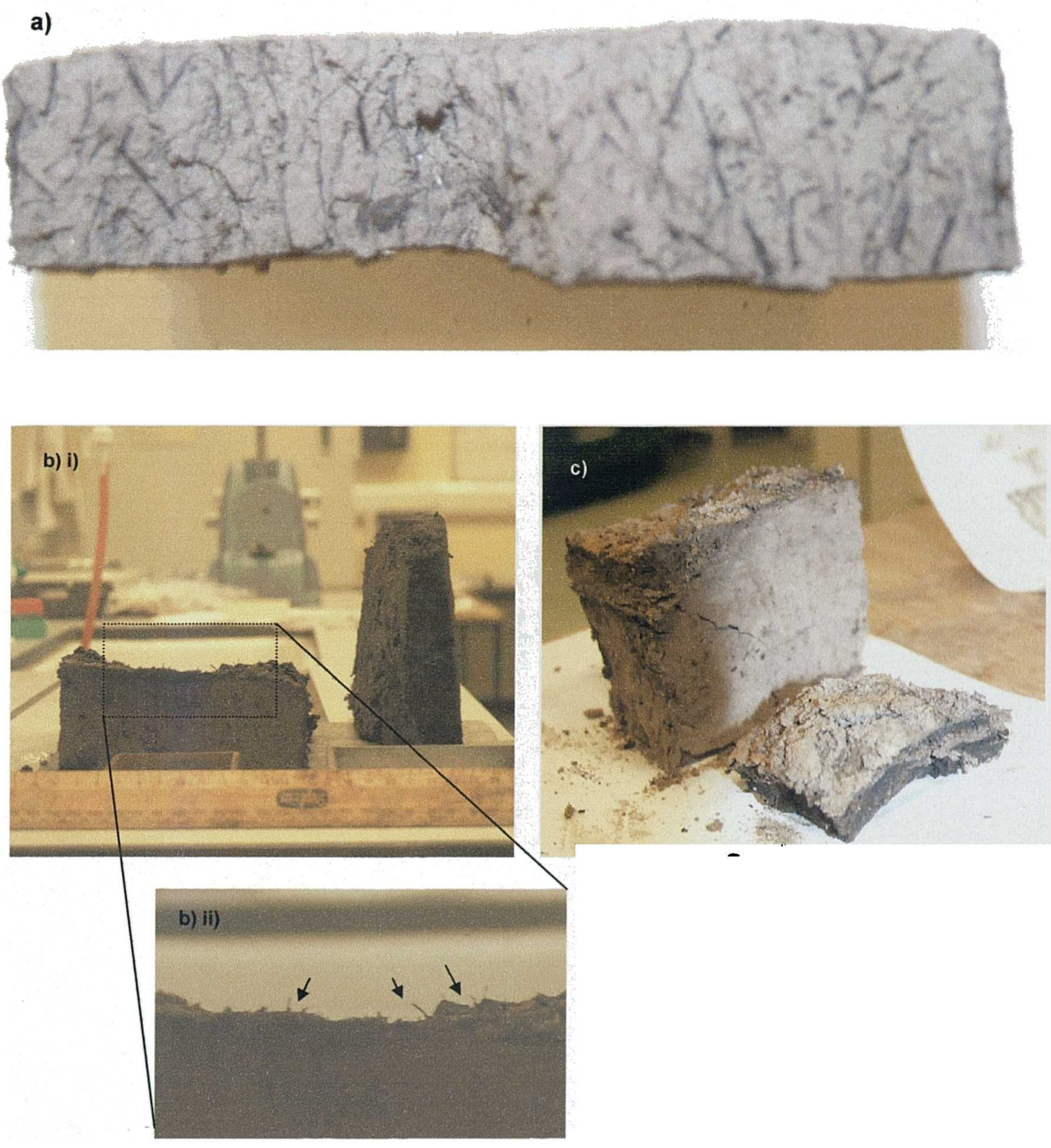
Concentrated laminar seepage extended across most of the 3 m faces at both Hart Hope and Langdon Head. In the former case, this occurred within the transition material immediately overlying the substrate, while in the latter a continuous seepage line was present some 5 cm below the peat-substrate interface. Point and diffuse seepage was also found within and at the upper boundaries of substrate at Iron Band and Feldon Burn. Seepage within an upper fibrous layer was also found at West Grain. In all cases, it appears that hydrological pathways were exploiting local layers of lower bulk density (such as fibrous layers), points of discontinuity between layers (namely transitions and boundaries), or forcing their way through substrate material. The presence of fissuring in the substrate (described in the following sections) may explain the presence of pipes and seepage in this relatively impermeable material.

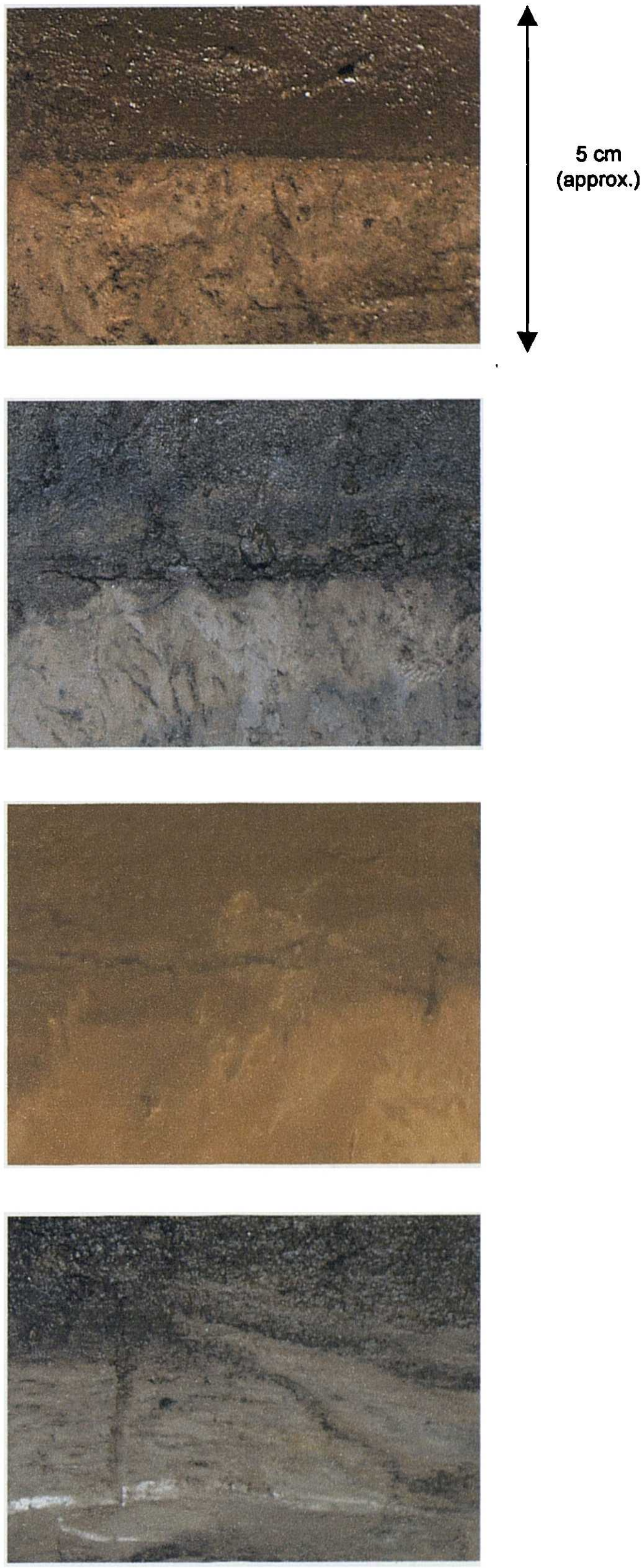
6.2.2 Determination of geotechnical characteristics

Six large box samples (22.5 x 21.5 x 8 cm) were collected from the Hart Hope site. The relative position of each sample in the soil column for Hart Hope is indicated on the stratigraphy diagram in Figure 6.15. During collection of the geotechnical samples, water appeared to discharge from the peat-substrate contact when pressure was applied to the overlying peat. Care was taken to avoid compression during the sampling of the columns used in the geotechnical tests. It was also found that large chunks (> 30 x 30 cm basal area) of peat were easily pulled from the underlying substrate, leaving saturated and undulating substrate beneath. However, the exact nature of the transition/interface could not be determined until sub-sampled in the laboratory. The substrate contained several bladed (b-axis generally < 10 cm) clasts, although not to the extent that full geotechnical samples could not be extracted.

Sub-sampling for shear tests revealed further characteristics of the materials. The peat corresponded to the pseudo-fibrous category of Akroyd (1964), with localised small root fragments generally less than 0.5 cm in diameter. The Troels-Smith and von Post classifications correspond to those for the Hart Hope head scar monolith between 0.85 and 1.10 m depth (Figure 6.15). Fibres were present, but they provided little or no resistance to cutting and little evidence of tensile strength. Some localised fissuring was evident, with cracks up to 10 cm in length, and 1-2 cm in diameter. Generally, the peat exhibited similar characteristics throughout the sample.

Figure 6.16. Hart Hope geotechnical samples: a) presence of sub-vertically oriented fibre trails in the substrate, b) fibres protruding from peat and substrate at plane of interface (arrowed in blow-up), c) thin layer of substrate attached but peeling from overlying peat.





a) peat substrate interface: contact is sharp (< 1 mm) and horizontal; fracture occurs easily at the contact between the two material types

b) peat substrate convoluted boundary: contact is sharp, but undulatory; preferential fractures occur at the 'average' upper limit of substrate intrusions into the peat mass (as shown)

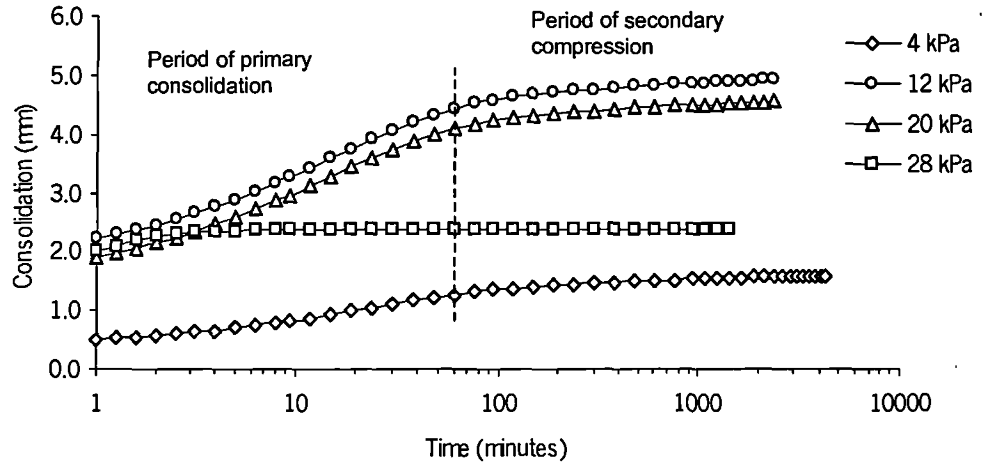
c) peat substrate transition: contact is graded (up to a few cm) and may be horizontal or undulatory; fractures occur preferentially within the peat mass although with no clear material control

d) warping and intrusion at the peat substrate interface: a tongue of substrate overlies a thin black diagonal band of peaty-mineral material - it is unclear how this has formed, but the disturbed nature of the interface is evident

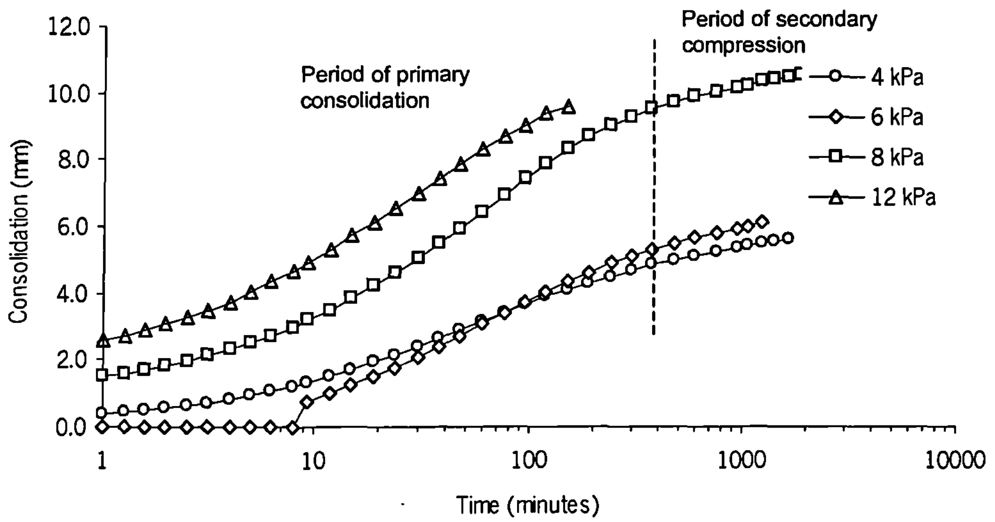
Figure 6.17. Photographs of peat substrate contact types.

Figure 6.18. Settlement, consolidation and compression for materials tested in standard shear box apparatus.

a) Consolidation stage for substrate samples (standard apparatus)



b) Consolidation stage for peat samples (standard apparatus)



The substrate material was generally soft and sticky, medium to light grey in colour, and with localised sandy nodules. Rust coloured lacey trails were apparent in a plane horizontal to the upper surface. Whether these were mineral veins or oxidised evidence of past biotic activity (e.g. earthworms) is uncertain. Evidence of past biological activity was prominent in the form of root-trails, aligned sub-vertically (less than 0.5 mm in diameter; Figure 6.16a). These were common throughout the samples. Smaller stones were absent, with only one larger, inclined clast impeding sub-sampling from one quarter of one of the two boxes. Sub-horizontal fissuring was evident in one of the two tins, with approximately half of the lower portion of one box unsuitable for sampling. Sub samples from each box were generally similar in characteristics.

The peat-substrate contact proved highly variable within each sample. An example of the contact variability in three dimensions is shown in Figure 6.3. The peat-substrate contact showed a sharp interface, a convoluted zone of transition, and a gentle gradation over only a few centimetres (Figure 6.17a to c). Fissuring was visible slightly above the contacts, often overlying sandy and silty inwashed layers. At the base of the peat layers overlying interfaces, a thin black layer was visible between the rest of the peat and the substrate. The origins of this layer are unknown, although they may relate to minor build up of humic products leached slowly to the base of the peat. In three of the eight exposed faces, warping and intrusion of thin clay layers was visible into the peat layer (Figure 6.17d). Although great care was taken during sub-sampling, only four samples could be extracted without disturbance to the interface or without the extension of fractures in the peat.

Once the last undisturbed sample had been removed from the interface tin for shearing, the remainder of the sample was broken open. The contact plane undulated with a shallow micro-relief. The surface was intermittently silty and sandy, with more of the rusty laced trails described earlier for the substrate samples. The upper face, and to a lesser extent, the lower face (Figure 6.16b) display protruding fibres, although none of the roots extend more then a centimetre from either face, nor are they particularly thick (< 1.0 mm). A thin skimming of clay (less than 0.5 mm thick) was found attached to some parts of the peat face. On drying, this peeled and flaked from the peat surface (Figure 6.16c).

The full test results matrix is shown in Table 6.8, with displacement distance to failure, test irregularities and sample notes.

Table 6.8. Geotechnical test matrix for direct shear tests on basal peat, interface and substrate

	Testing scenarios		Consolidation			Shear			
Profile layer	Equivalent peat overburden (m)	Drainage conditions	Apparatus (standard/small)	Settlement (mm)	Duration (hrs:mins)	Strain rate (mm hr^{-1})	Strain to 'peak' strength (mm)	Shearing stress at peak strength (kPa)	Notes
Basal peat	0.4	undrained*	standard	5.4	28:00	10.8	2.5	21	
	0.6	undrained*	standard	6.0	20:00	10.8	3.3	32	
	0.8	undrained*	standard	10.9	25:00	10.8	2.5	40	
	1.0	undrained*	standard	not measured	n/a	10.8	3.0	38	failure of standard apparatus
	1.2	undrained*	standard	9.6	3:00	10.8	2.4	56	consolidation stage interupted
Interface	1.2	undrained	small	not measured	n/a	10.8	5.0	14	
	2.0	undrained	small	not measured	n/a	10.8	3.5	27.5	
	2.8	undrained	small	not measured	n/a	10.8	3.5	22.5	
	3.6	undrained	small	not measured	n/a	10.8	3.5	20	
Substrate	0.4	drained	standard	1.5	72:00	0.24	4.0	27	
	1.2	drained	standard	4.9	40:00	0.24	4.5	60	
	2.0	drained	standard	4.5	40:00	0.24	3.0	90	
	2.8	drained	standard	2.4	24:00	0.24	5.0	22.5	soft sample
	2.0	undrained	small	not measured	n/a	10.8	5.5	12.5	soft sample
	2.8	drained	small	not measured	n/a	0.24	5.0	25	
	3.6	drained	small	not measured	n/a	0.24	4.0	24	
	1.2	undrained	small	not measured	n/a	10.8	5.0	12	
	2.0	undrained	small	not measured	n/a	10.8	4.1	17.5	
	2.8	undrained	small	not measured	n/a	10.8	4.0	15	soft sample

* the structure of the peat is such that these tests are effectively drained tests

6.2.2.1 Loading characteristics of peat and clay

Of the 19 full tests conducted, only the consolidation stages of those in the standard shear box apparatus could be logged. Figure 6.18a and b show consolidation curves for the substrate and basal peat.

In the substrate, immediate settlement was extremely rapid, occurring in under one minute (and hence not visible on the log time plots in Figure 6.18). Primary consolidation was largely complete after approximately two hours, with minimal secondary compression over the 24 hours until initiation of the shearing stage. The sample loaded at 28 kPa (2.8 m equivalent peat overburden) appeared anomalous, with primary consolidation complete after only a few minutes, and no apparent secondary compression. The extent of consolidation across all four samples also appeared unusual, with the 20 kPa sample consolidating less than the 12 kPa sample, despite an equivalent period for consolidation. Consolidation proved variable throughout the full sample set, and samples were not rejected on the basis that unpredictable behaviour might be a feature of the materials tested.

Peat consolidation, was unexpectedly more straightforward, with rapid immediate settlement, but a longer period of primary consolidation. Secondary compression was still continuing when the consolidation stages were truncated. The extent of consolidation was considerable in the cases of the heavier loads (10 - 12 mm in a 32 mm deep sample, or 30 - 40%), and still significant for the lower loads (5 mm, 25%). In the case of the 12 kPa load, truncation of the consolidation stage was particularly early. This was necessary to ensure that the peat mass did not reduce in volume such that the upper plates of the test cradle interfered with the shearing process.

6.2.2.2 Relative shear strength characteristics of peat, clay and the peat/clay interface

In total, 19 tests were conducted, ten on the substrate, five on the basal peat, and four on the peat-substrate interface. Examples of stress-strain plots are shown for the undrained peat and drained substrate tests (Figures 6.19a and b), both sets carried out in the

Figure 6.19. Examples of stress-strain curves for different layer types: a) brittle substrate failure; b) non-brittle (ductile) peat failure; c) possible stick-slip failure in interface

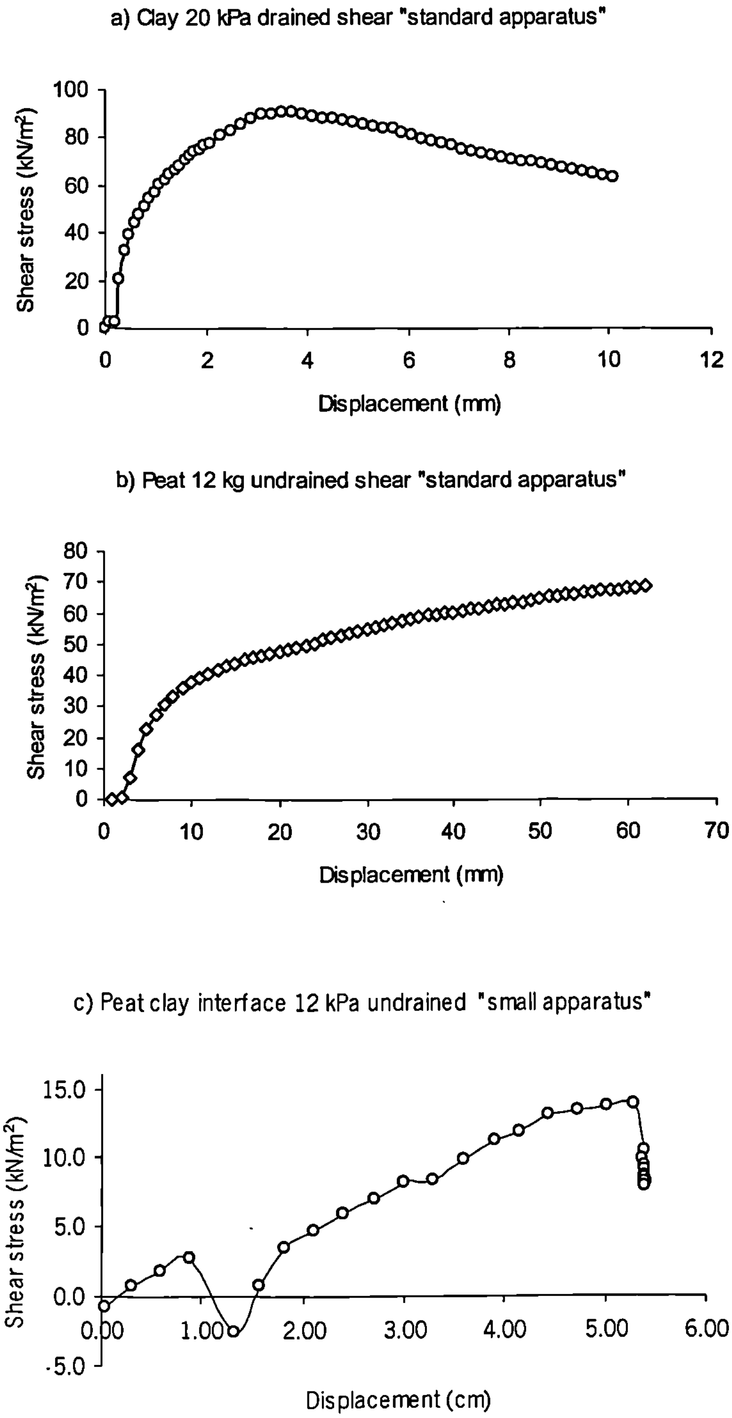
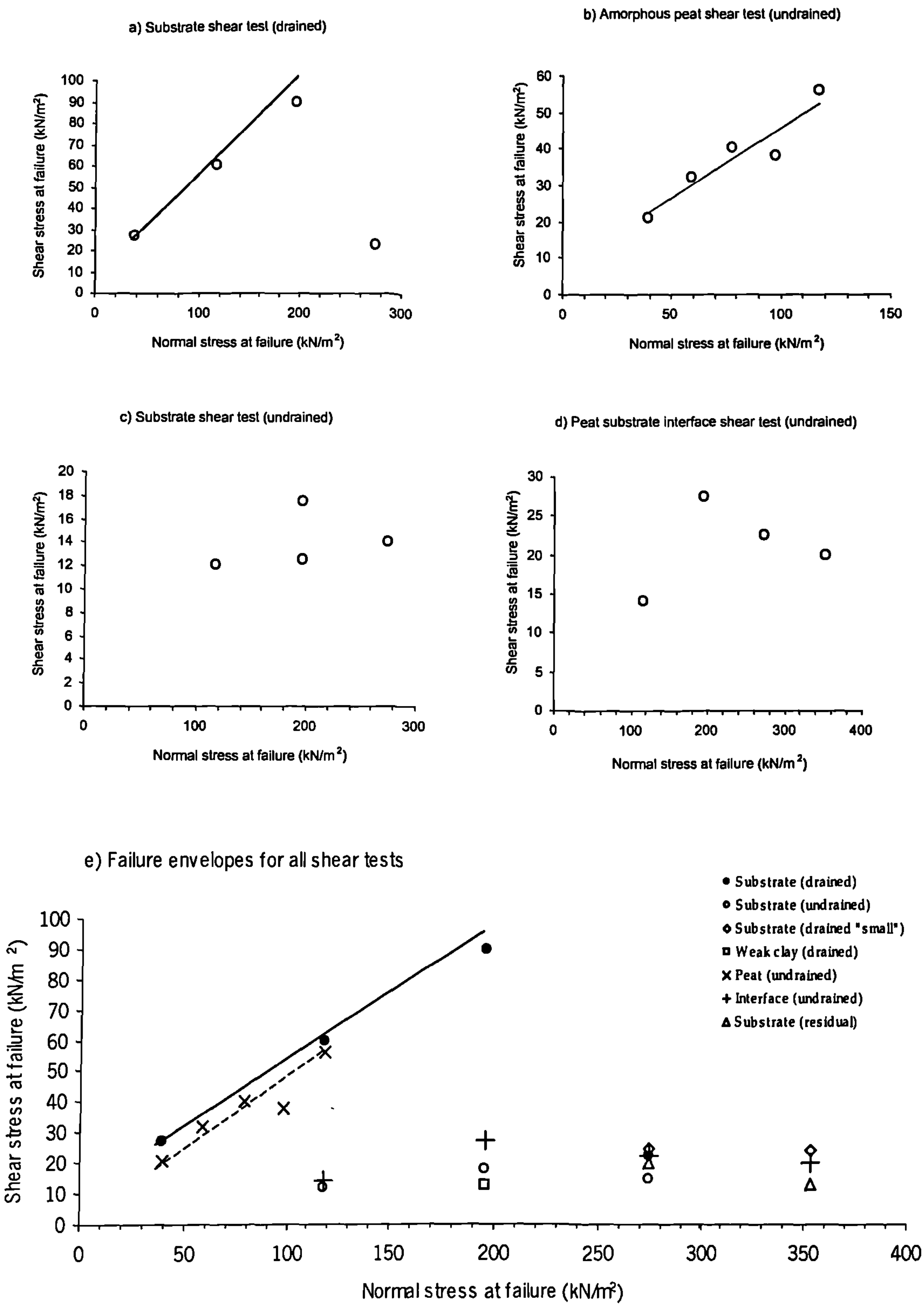


Figure 6.20. Shear envelopes for all tests.



standard shear box apparatus. Samples were tested at normal loads (σ) corresponding to 0.4, 1.2, 2.0 and 2.8 m of saturated peat overburden, and under drained conditions. The two samples at the lowest peat depth equivalents experienced non-brittle (or ductile) failure at under their peak strengths, and at displacements of approximately 3 mm. Settlement continued throughout the shearing stage, levelling off at approximately the same strain as failure. The samples under greater equivalent peat depths demonstrated brittle failure at peak strength, and at approximately the same strains. Transducer errors prevented assessment of settlement rates during shearing for these latter samples. The failure envelope (or Coulomb envelope) for the drained substrate tests is shown in Figure 6.20a. The 28 kPa loaded sample is excluded in the calculation of the shear strength parameters ϕ and c, as it was noted as 'soft' during sampling, and produced anomalous results under both the consolidation and shear stages. Using the three remaining samples, the substrate material obeys Terzaghi and Peck's (1967) relationship between maximum shearing resistance and normal stress, giving values for ϕ of 21° and for c of 11.75 kN m^{-2} (Table 6.9). These values correspond closely with those produced by Carling (1986) for North Pennine substrate material, tested under similar conditions. Under drained loading, the presence of a cohesion intercept indicates overconsolidation in the substrate, which is possible given the relatively low normal loads used in testing. Attempts to complete and extend the sequence of drained tests using 28 and 36 kPa loads on the small shear box apparatus produced similarly low non-peak strengths for two further substrate samples.

Undrained tests conducted on the substrate show similar shear stress/displacement curves to those for the drained material, but with failure induced at far lower shear stresses. All tests exhibit a peak strength followed by the onset of a slow decline in shearing resistance. The failure envelope indicates an angle of shearing resistance of virtually zero (Figure 6.20c), with the cohesion intercept equivalent to an undrained shear strength derived from apparent cohesion c_u of 17.1 kN m^{-2}. Again, this is as expected for an undrained test on a saturated, predominantly clay sample. In both drained and undrained scenarios, 'soft' substrate was tested (normal and shearing stress values shown on Figure 6.20e). Attempts to differentiate 'soft' and 'stiff' clays on the physical basis of texture proved unsuccessful however. Particle sizes indicated that clay, silt and sand composition is relatively uniform across samples, corresponding to silty clay loams. Differences in behaviour to applied loads may hence be a product of either differing stress histories or of structural differences caused by chemical processes acting on the substrate material, such as the effects of localised humic acids. Possible reasons for the variability in substrate behaviour are discussed in section 6.3.

The peat samples were tested under undrained conditions only, partly in response to rapid settlement both in the consolidation stage and occurring under shearing (see Figure 6.20b), and partly because the structural properties of peat are complex with regard to pore water pressure generation during testing (see section 6.3). The values on the shear stress/displacement curve for the basal pseudo-fibrous peat are consistent across a range of peat overburdens, equivalent to between 0.4 and 1.2 m saturated peat depth (e.g. Figure 6.18b). All failures are ductile, without attainment of peak strength under the strains possible. The failure envelope for the peat material corresponds closely to that produced for the substrate, with ϕ and c equivalent to 23° and 5.0 kN m^{-2}, respectively (Table 6.9), although the contribution of cohesion to shear strength is significantly lower. These values also correspond with values produced by Carling (1986) for [pseudo] fibrous peat from the Langdon Head site. Unlike Carling's tests, the response of peat to shear stresses appears consistent and predictable.

Four undrained interface tests were conducted, for which an example stress/ displacement curve is shown in Figure 6.19c. On retrieval from the shear box apparatus, the failure planes had correctly aligned with the two halves of the boxes, and results described here are assumed to be as interface failures.

The shear stress at failure varies to a greater extent than for the substrate undrained tests, and it is not possible to confirm the presence of a negligible angle of shearing resistance under heightened pore-water pressures, nor is it possible to establish a cohesive strength with any certainty. An unreliable c_u of 11.08 kN m^{-2} is greater than that produced for the substrate however. The example in Figure 619c is highlighted for interest, as it appears to exhibit a stick-slip stress-strain curve, which may relate to the existence of a pre-existing slip-plane at the interface unnoticed during sampling. In such a case, shearing resistance would be generated by an irregularity in the failure plane (such as a woody protrusion, small stone, or locally stiff material). As only a small percentage of the area under shear, this would be overcome at low strains (such as the 1 cm on Figure 6.19c), and shearing resistance would then be generated at a rate more representative of the wider sample properties. At the peat-substrate interface, there is good reason to assume irregularity in the nature of contact.

Attempts to derive residual strengths are also shown in Figure 6.20 ("substrate residual").

However, tests were limited by machine time and wastage of the sample under repeated reversals in the small shear box apparatus. For the two sets of reversals undertaken, shear stress at failure was lower for the equivalent-load, equivalent-drainage non-residual substrate samples. This may suggest that although the substrate did not fail at peak shear strength in all cases, it may still have failed at greater than its residual strength.

Further, limited geotechnical and index property tests were conducted to elucidate relationships between the results derived from the shear tests and the properties assessed in the bulk profiles. Particle size analysis suggested relatively close correspondence between sheared samples, with clay, silt and sand contents clustering around 34%, 45% and 19% respectively. These correspond to a silty clay loam in texture, and not a 'clay' as the materials beneath peat slides are commonly referred to. Preliminary data concerning consistency limits for a sample of the substrate material gave values for the liquid limit of 55% and the plastic limit of 32%. However, derivation of the liquid limit did not provide consistent results between tests. This is unsurprising given the variability in results derived from the substrate shear tests.

Figure 6.21 illustrates a micro-profile at centimetre resolution through the peat-substrate interface. It shows good agreement between two adjacent sample columns for loss on ignition, wet bulk density and gravimetric moisture content, and suggests that the four samples used for interface testing are likely to have been comparable.

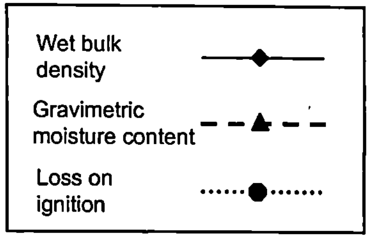
6.3 Discussion

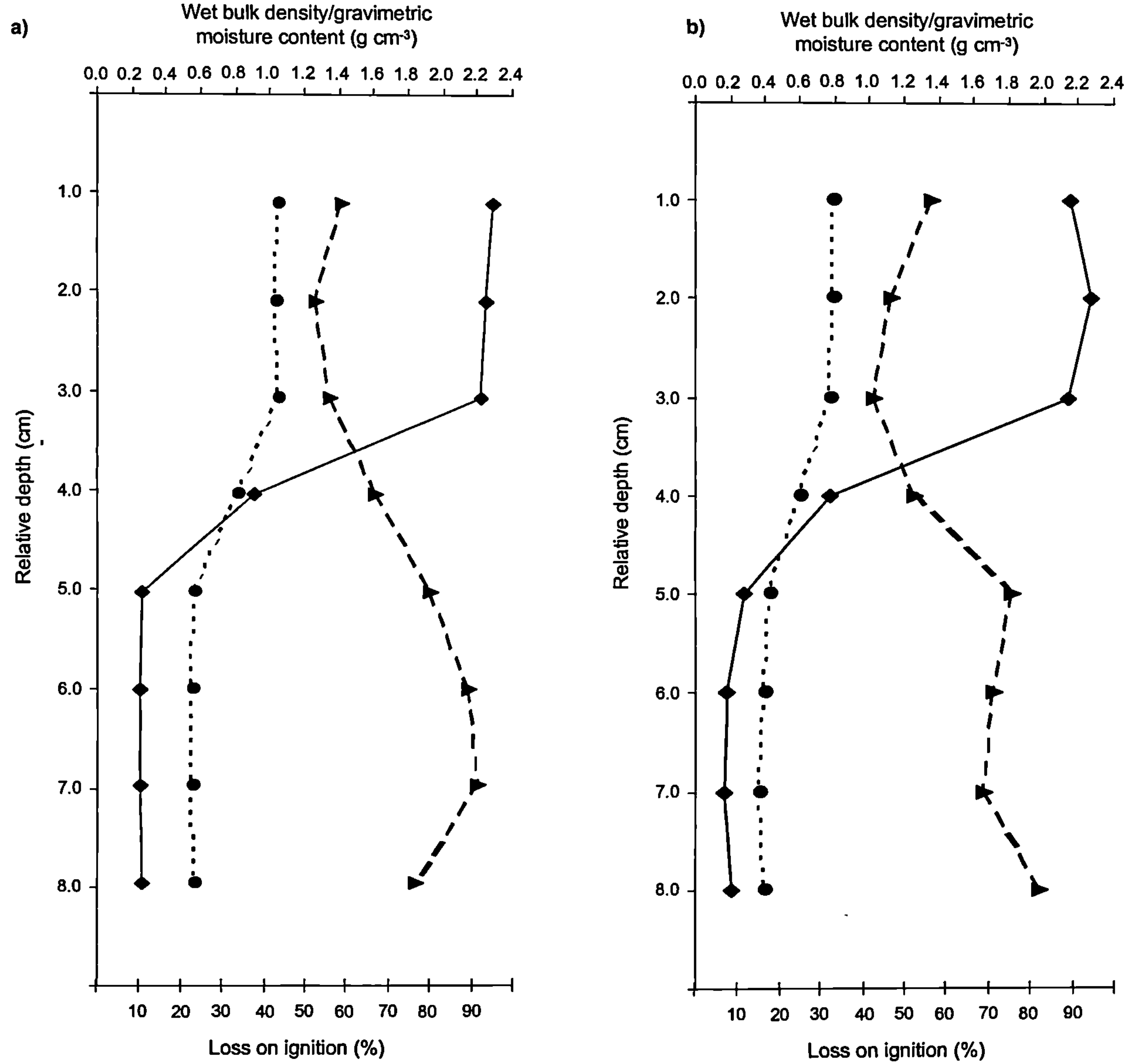
The objectives stated at the outset of this chapter concerned three main issues: definition of stratigraphic units particular to peat and substrate in areas affected by peat slides in the North Pennines; quantification of their material properties; and evaluation of the effects of these material properties in encouraging failure or stability. The remaining sections consider the results described previously in the context of these aims, and in the light of existing research into peat slide mechanisms.

6.3.1 The classification of North Pennine peat slide stratigraphic units

Peat stratigraphy is characterised by at least two, and more usually three distinct layers

Figure 6.21. Hart Hope peat-substrate contact zone micro-profiles. Measures of bulk density, moisture content and loss on ignition correspond closely for the two-sub-samples.





(Figures 6.12 to 6.15). The upper comprises a relatively undecomposed, usually highly fibrous (but occasionally mossy) mat of surface vegetative matter. This extends for between 5 and 20 cm of the upper peat profile. The second layer consists of a more decomposed matrix, in which fine fibres are common, or in which coarser fibre bundles are present. At some sites, fibres may be intact enough that they provide the wider material mass with an element of tensile strength. This is usually associated with fibre bundles rather than fine fibres, and the former may exist in layers beneath the acrotelm of up to half the total peat mass depth. These layers correspond to Akroyd's (1964) 'fibrous' class. At other sites, where fine fibres dominate, structure may be more 'apparent than real' (Hobbs, 1986), and the peat corresponds to Akroyd's 'pseudo-fibrous' class. Both layer variants grade (abruptly in the case of the 'fibrous' layer) into a third layer, pseudo-fibrous to 'amorphous' in character. Fibres are fine, and scarce to absent with no tensile strength, and the lowest units in proximity to the substrate exhibit very high humification values. The only undecomposed matter remaining in these layers are fragments of wood.

The fibre content of peat is highly significant in the matter of peat mass strength. Fibres are regarded as imparting peat with most of its 'apparent' cohesion, and hence its tensile strength (e.g. Helenelund and Hartikainen, 1972; Landva, 1980; Landva and Pheeney, 1980; Eggelsmann *et al.*, 1993; Termaat, 1994). Various authors have attempted to quantify fibre strength, often through novel approaches. Helenelund and Hartikainen (1972) used a modified 'helical' auger to conduct tensile (and compressive) strength tests on peats of various fibre content. By alternately screwing in and retracting the auger at a variety of angles to the ground surface they demonstrated the anisotropy of peat tensile strength. Strength in the horizontal plane was shown to be considerably greater than in the vertical plane. This has possible implications for detachment of the peat mass from the underlying substrate (where fibres extend to the base), as well as for the ease with which moving peat masses buckle and shear during transport.

The anisotropic strength afforded to peat by its fibres may provide little structural support at the peat base, but may prevent the spread of fractures up into the upper, more fibrous layers. It is possible therefore that there is a differential in peat mass strength between the upper, fibrous and less humified layers, and the lower more humified, less fibrous layers. Hanrahan (1954) supports this, suggesting that more humified peats more readily develop shear planes, while Hobbs (1986) attributes the loss of both tensile and shear strength to increased humification.

Fibres have also been responsible for much confusion in the discussion of peat strength, particularly in the field of engineering. Fibres have been equated with cohesion (e.g. Hardy, 1968), hence 'apparent cohesion', although tensile strength is not the cohesion upon which the laws of Terzaghi and Coulomb are based. Fibre-related difficulties in the discussion of peat mass strength include non-linearity of the failure envelope, occurrence of peak strength after large strains, anisotropy of shear strength, and the effects of fibre reinforcement (Head, 1982; Termaat, 1994). These have led a number of authors (Head, 1982; Hobbs, 1986; Bell, 2000) to state that peat does not conventionally obey laws used in wider soil mechanics approaches. Consequently, a tendency to avoid peat testing, whether fibrous *or* amorphous has resulted. The results summarised in this chapter show that non-fibrous peat may respond to shearing stresses in a predictable manner, and are discussed shortly.

The distribution of locally highly tensile units throughout the profile depth may afford the entire profile greater coherence than if the fibrous units were concentrated at the surface of the peat mass. The significance of layering for peat mass strength has been alluded to on a number of occasions. Landva and Pheeney (1980) note that the variability in layer properties afforded by differing fibre contents will cause strength variations in the peat mass as a whole. Peat mass movement literature in general supports the idea of at least a dual-layer concept (outside the acrotelm/catotelm system) in bog bursts particularly, but also in peat slides (see Chapter 2, section 2.2.1). When each core profile is grouped according to like properties (i.e. separated by the largest discontinuities), most sites exhibit their major boundary at the peat substrate contact. However, some sites in which there are major changes in fibre content and humification mid-profile exhibit major boundaries within the peat mass, potentially supporting the idea of a two-phase peat system in failing peat masses. The significance of this layer is likely to control the mode of break-up of the peat mass, rather than the location of the shear plane.

The complexity of the peat profile may play a part in the development of discontinuities and planes of weakness. Hydrological pathways such as pipes and seepage layers form preferentially at unit boundaries within the peat mass, and at its base. Under conditions in which the peat mass is saturated, pipes and seepage layers will become active, and under appropriate hydrostatic pressures, may exploit the tendency of the peat to fracture and generate horizontal and vertical planes of weakness (dependent upon the pipe cross sections, phreatic or cylindrical). Equally, cycles of wetting and drying in the vicinity of such ephemeral airways may exploit the discontinuities between differing peat layers, causing them to expand and contract at different rates. Small variations in dry and wet bulk density, suggesting relative uniformity of peat conditions may be associated with large variations in shrinkage. Equally, peat surface volume changes associated with drying may produce irreversible cracking and weaknesses, which may in the future be exploited by overland flow.

The importance of discontinuities in the peat mass as hydrological pathways may be significant in the generation of destabilising water pressures. Permeable materials may permit seepage, in which movement of water occurs, usually horizontally. Seepage imparts a frictional drag in the direction of movement on the particles through which it occurs, counteracting gravitational forces. Where seepage is extensive enough, and gravitational forces are completely negated, the material exists in a state of zero effective strength, and disturbance to the material results in failure. Several authors have suggested that despite the lack of a dense particulate matrix in catotelm peat, these more humified layers have very limited permeability (Boelter, 1968; Paivanen, 1973; Rycroft and Williams, 1975; Hobbs, 1986; Baird *et al.*, 1997). Hence, there may be preferential seepage at the contacts between peat layers of different origin, and associated destabilising forces.

6.3.2 The material properties and engineering behaviour of North Pennine peat slide stratigraphic units

Bulk properties were derived as a means of quantifying the layer properties throughout the peat profile. All sites exhibit their lowest peat bulk densities (whether wet or dry) in the acrotelm, stabilising thereafter to values just above 1 g cm^{-3} throughout their remaining profile depths (Figures 6.9 to 6.11). Incorporation of mineral matter, associated either with disturbance layers within the peat mass, or with the peat mineral substrate, see bulk densities increase, and moisture contents and organic matter contents decline. Gravimetric moisture contents are stable with depth, while volumetric moisture content and dry bulk density fluctuate with humification and fibre content. Fibre bundles and extensive fine fibre masses cause local declines in bulk density.

Absolute values of bulk density are unlikely to be illustrative of tendency towards failure. Values quoted for North Pennine failures within this thesis (Table 6.7), and other published values (e.g. Carling, 1986; Alexander *et al.*, 1986; Hendrick, 1990; Wilson and Hegarty, 1993) fall within the ranges quoted for unfailed peat (e.g. Galvin, 1976; Hobbs, 1986).

However, the association of bulk density with moisture content and fibre content (Figures 6.12 to 6.15) may allow its use as a surrogate for these values, without the need for use of extensive classification systems such as von Post and Troels-Smith. Moisture contents, whether volumetric or gravimetric support high values through much of the peat depth. The addition of further water during wetting is unlikely to significantly increase the weight of the peat mass as a result. Loading induced by increased moisture contents alone is unlikely to be significant. The fact that bulk density appears unaffected by depth within the peat mass, supports the idea that peat is quite capable of holding its own weight when undisturbed. It does this through the structural support provided by held cell-water (Wilson, 1972). Conversely, the tendency for bulk density to increase with depth in some of the underlying substrate samples suggests that peat depths may be more important in controlling the stresses experienced by the substrate.

As a point of note, comparison of both wet and dry bulk densities, and of gravimetric and volumetric moisture contents suggests that all measures are necessary to properly evaluate layer discontinuities. Individual measures were shown to vary with structural properties associated with the von Post and Troels-Smith schemes, although not always consistently between samples. The under-representation of moisture contents in the substrate relative to peat when using w (as opposed to w_v) suggests that volumetric calculations should always be used to compare the two materials (Skaven-Haug, 1972).

The strength characteristics of pseudo-fibrous to amorphous peats in the basal part of the peat profile are relatively consistent, and are very similar to values derived for the underlying substrate under similar testing conditions. There is little apparent cohesive strength without the presence of fibres, and inter-particle chemical bonding would be minimal.

The angle of shearing resistance for the peat sample tested suggests stability on slopes under 23°, a value that although experimentally robust, refutes the existing data set concerning morphometric controls at slide sites (see Chapter 3, section 3.2.3). Most failures occur on slopes between 5° and 20° in gradient. It is likely therefore, that factors other than the intrinsic qualities of the hillslope materials are also responsible for failure. This is to be expected, given that a vast majority of the blanket peat in the North Pennines has not experienced mass failure. Carling (1986) was able to derive shear strength parameters for fibrous peat at Langdon Head, though he states that results were subject to scatter and unreliable. However, this may be explained by the 'fibrous' nature of the peat, relative to the pseudo-amorphous peats tested at Hart Hope. Both peat types tested are within a few kilometres of one another, but local differences in peat at each site may have yielded samples differing in fibre content. Landva (1980) also attributes the inappropriateness of the vane test to the fibre components of the peats he tested. A tensile strength value of 5.5 kN m^{-2} for an Escuminac peat (fine fibrous to pseudo-fibrous) corresponds well with the cohesion value for the Hart Hope peat (Table 6.9), and indeed, Landva suggests that the cohesive component of strength and tensile strength may be the same thing at low to normal loads (as used in the tests described earlier).

Observations suggest that under remoulding, the fibre component of pseudo-fibrous peat samples was destroyed completely. It is probable that the apparent cohesive strength of peat becomes less 'apparent' with increasing humification, and that in the absence of complete decay (i.e. at H_9 or less), remoulding may remove any cohesive element of peat strength. Given the fibre distributions along core profiles noted at most sites, this is only likely to occur in the most basal layers where humification is highest. Furthermore, the decline in the liquid limit of peat (not quantified here) associated with increasing humification (Hobbs, 1986; Eggelsmann *et al.*, 1993) would increase the tendency of peat to deform under relatively unchanging conditions, and hence remould. Further shear tests on completely amorphous peats would elucidate such a mechanism.

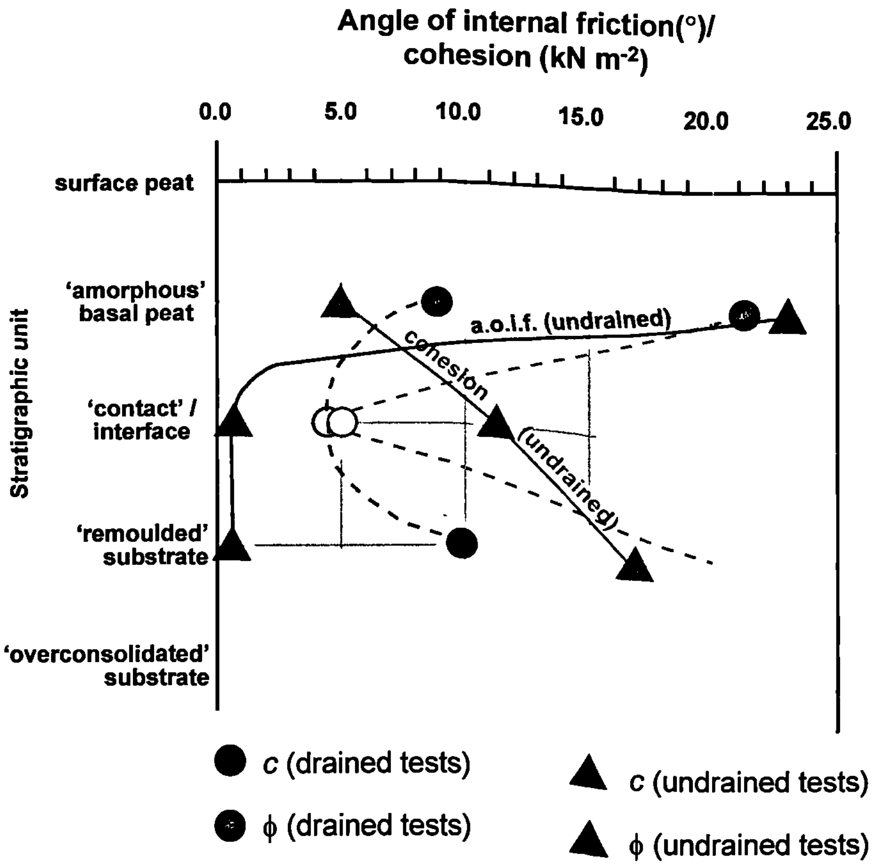
Testing conditions were selected according to likely field conditions at the time of failure. The consolidation stage for each peat sample followed that described many times before in peat geotechnical literature (e.g. Akroyd, 1964; Glynn *et al.*, 1968; Solopov *et al.*, 1968; Wilson, 1972; Hobbs, 1986; Bell, 2000), namely rapid immediate settlement and relatively fast primary consolidation followed by lengthy secondary compression. Despite the considerable volume losses associated with the consolidating loads, the shear tests produce stable results under undrained shear conditions. However, Wilson (1972) has suggested that it is magnitude of loading rather than cyclicity that is important in determining the compressive strength of peat masses. Given the similarity of peat strengths to those for the substrate (described shortly), and the likelihood of attaining large enough loads to satisfy criteria for compressive failure (loads associated with construction rather than with natural events), excessive loading seems to be an unlikely trigger for slide masses. It is probable therefore that properties of the peat mass not considered in shear testing may be of relevance to failure initiation. For example, observations suggest that wood fragments may act as foci for weakness in the basal peat plane, allowing sub-

Table 6.9. Shear strength parameters for all materials.

Layer type	Consolidating load range (kN m^{-2})	Equivalent peat overburden depth (m)	Drainage conditions	Angle of internal friction (deg)	Cohesion (kN m^{-2})	Author
Basal peat	4 - 12	0.4 to 1.2 m	Undrained	23.0	5	Mills (unpub)
Peat substrate interface	20 - 36	2.0 to 3.6 m	undrained	1.0	11.08	Mills (unpub)
Clay substrate	20 - 36	2.0 to 3.6 m	undrained	1.0	17.1	Mills (unpub)
Clay substrate	4 - 28	0.4 to 2.8 m	drained	21.0	11.75	Mills (unpub)
Sand free clay substrate	13 - 68	1.3 to 6.8 m	drained	5.0	4.28	Carling (1986)
Sandy clay substrate*	13 - 68	1.3 to 6.8 m	drained	23.1	9.75	Carling (1986)
Fibrous peat	13 - 68	1.3 to 6.8 m	drained	21.6	8.74	Carling (1986)
Pale clay substrate*	?? - 30	?? To 3.0 m	drained	26.5	2.75	Dykes and Kirk (2001)

* starred results not used in Figure 6.22.

Figure 6.22. Envelopes for cohesion (*c*) and angle of internal friction (ϕ)for peat slide stratigraphic units.



horizontal fractures to propagate with relative ease. Similarly, Allen (1999) notes the importance of wood fragments in generating defects followed by sub-horizontal failures in peat flake failures in coastal deposits.

Mention should be made of the relevance of drainage conditions during shearing, as determined by strain rates. The relatively open structure of peat (given its high moisture contents) means that tests conducted at high strain rates are not necessarily truly 'undrained'. Collapse of cell structures under shearing stresses (Wilson, 1972) may release water and allow drainage, though this will also involve an increase in pore water pressures (having the 'effect' of an undrained test, if not for the same physical reasons). Correspondingly, Hanrahan and Walsh (1965) suggest that the response of peat to strain is independent of strain rate.

The North Pennine peat substrate is clayey in nature, with a texture and clastic component corresponding to that of till (Bell, 2000). The layers likely to be involved in mass movement range from relatively stiff blue-grey clays to locally ductile and sandy light grey clays. The latter are easily cored and point to the presence of local weak 'cells' of material in the upper substrate. Extensive stone layers are usually found within a few centimetres of the peat substrate contact. Field evidence suggests that these are not by and large transported, and hence it is the properties of the overlying substrate that are of relevance in peat mass movement initiation.

The properties of till are different to those of clay (the term used, correctly or incorrectly in previous published studies), not least because of the stress histories incumbent upon them from glacial activity, and their subsequent patchy reworking by solifluction and frost heave (Warburton, 1998). The substrate materials exist in various textural states (remembering that sheared samples were generally selected for similarity, not anomaly), and the presence of large, sub-horizontal clastic material and fissures, although unquantified here, is likely to be significant (McGown *et al.*, 1974). Shear strength parameters derived from drained tests (in which excess pore water pressures were not generated) suggested stability of the substrate material on slopes under 21° under saturated conditions. Undrained tests, simulating a load induced increase in pore water pressures and consequent decline in frictional strength illustrate a still considerable cohesive strength of 17.1 kN m^{-2}. This again suggests that an explanation for failure beyond merely slope and water content is required. Remoulded values were inconclusive given the lack of a complete test sequence, although when stress/strain curves were compared with similar loads and drainage conditions, shear stress at failure appeared lower in both cases.

Preliminary data suggest that there may be a large range of liquid and plastic limits for the varying substrate materials (e.g. stiff versus soft tills), and that there will exist localised 'hotspots' of soft clay liable to flow deformation under infrequent but high stresses. Again, these locally weak layers may relate to former areas of solifluction which may have locally sorted sediments into surficial coarse and fine patches.

The peat-substrate contact that joins these two layer types may comprise a layer in its own right, a graded transition or turbulent boundary, or it may represent a thin discontinuity or interface. Most sites exhibit a variety of contact types, with transition contacts dominating at low peat depths (often near blanket margins) and interfaces prevalent at intermediate and greater depths. Transition layers and turbulent boundaries are normally thin (< 5 cm depth), with rapid increases in mineral content within the basal peat mass.

The presence of a mineral fraction in the basal transition peats appears to give bulk properties greater consistency. Hobbs (1986) suggests that while the liquid limits for well humified peat are often low, the addition of minerals to the peat mass lends the material plasticity, and hence, perhaps stability. Bell (2000) supports the idea of an increase in shear strength with increasing mineral content, though does not cite data to support this claim. However, if both these assertions are true, it is possible that transition peat represents a relatively stable layer within the profile as whole.

6.3.3 The relative significance of North Pennine peat slide stratigraphic units in controlling peat mass movement mechanisms

Stratigraphic, bulk property and geotechnical data support the differentiation of North Pennine peat-to-substrate profiles into characteristics stratigraphic units, each with properties significant in the control of slope stability. These units may be divided according to their mode of origin. Three main units comprise the overlying peat component of the profile. The surface acrotelmic 'fibrous' unit is characterised by high fibre contents and associated tensile strength, irregular shear strength and is hydrologically significant in determining the presence of pathways from surface peat to depth (through cracks or pipes). The upper catotelmic 'pseudo-fibrous' unit is characterised by a pseudo-fibrous to occasionally amorphous matrix, with moderate tensile strength, irregular shear strength, and localised weak layers through which hydrological pathways may propagate in response to excess water contents. The basal catotelmic 'amorphous' unit is amorphous to pseudo-fibrous, with very low or absent tensile strength (which is lost completely on remoulding), wood fragments and the capacity to fracture readily both sub-horizontally and vertically under stress.

Beneath the peat units is found the peat-substrate 'contact zone'. This is characterised by a peat-mineral contact that varies spatially between a graded transition and sharp interface. Where the contact is graded, the peat-mineral transition material exhibits an intermediate cohesion and shear strength. Where the contact is an interface, the overlying 'amorphous' basal material has a minor mineral component and adheres weakly to the substrate. Only the weaker interfaces were subjected to shear tests in this study.

The substrate is divided into an upper 'remoulded' till unit, and a lower, 'over-consolidated' till unit. The first is characterised by a predominantly stiff, but locally soft, fractured and ductile silty clay loam that has to a greater or lesser extent been reworked by subaerial weathering and erosion in the aftermath of glaciation. It has moderate shear strength, and relatively high cohesion. The lower substrate layer is characterised by stiff, clastic clayey material of higher strength, and generally stable over the slope angles found in the North Pennines.

Given the identification of these stratigraphic units, the three hypotheses cited in section 6.0 may be reconsidered in the light of material evidence. These were:

i) There is a clear envelope of material strength exhibited at peat slide sites, in which the substrate is the weakest layer, the peat-substrate contact an intermediate layer in strength, and the peat mass the strongest layer;

ii) Heavily rafted sites (see Chapter 5) result from peat profiles characteristic of higher internal strength than non-rafted sites;

iii) Peat slide and bog burst masses exhibit consistent and differing characteristic bulk properties;

Each hypothesis is now considered in turn. Figure 6.22 shows c and ϕ values plotted for each layer for which tests have been conducted, as functions of drained and undrained testing. Drained and undrained parameters are linked through each layer to produce envelopes of c and ϕ for each drainage scenario. Carling's (1986) values for a similar, local material have been used to supplement results acquired in this study. The sandy free clay substrate represents the closest material layer to the interfaces tested in this study, and is used to represent the contact zone.

Figure 6.22 indicates that if the shear strength parameters of cohesion and angle of internal friction are considered separately, they exhibit definable envelopes from peat to substrate. Under drained conditions, in which slope failure would be the culmination of long-term progressive weakening, 'amorphous' peat and 'remoulded' substrate are stable within the North Pennine range of relief. Only steep slopes (>23°) at the most blanket marginal valley sides would experience failure. Long term processes responsible for shear failure might include progressive creep deformation of the substrate, to a point at which the remoulded strengths exhibit a fall of ϕ to below a threshold of slope stability. Cohesive strength is relatively consistent through the peat-substrate contact, and therefore the angle of internal friction is chiefly responsible for differing bulk material behaviour between units.

In undrained conditions, in which failure results from rapid shear and generation of high pore-water pressures (e.g. Carling, 1986; Dykes and Kirk, 2001), the ϕ is significantly lower in the 'contact' and 'remoulded' units. Slopes in excess of 5° may be unstable, and both the 'contact' and 'remoulded' units may experience shear failure. Cohesive strength rises from peat to substrate, but a combination of intermediate cohesion and low angle of internal friction suggest that the contact is the unit most liable to failure. This is consistent with field reports of failure plane location. However, locally weak substrate may also fail internally, leading to the transport and deposition of blocks with clayey material at their bases. This is also consistent with the occasional reports of clay coated blocks at some North Pennine sites (Crisp *et al.*, 1964; Carling, 1986).

The second hypothesis suggests that peat slide morphology is dependent upon properties specific to each stratigraphic unit. Hence, morphology will be primarily controlled by the qualities of the peat, which comprises the majority of transported volume. The most heavily rafted sites exhibited a greater tendency towards fibrous layers throughout at least half of their peat depth, although these theoretically cohesive units were not exhibited at all rafted sites. It is probably the case that low slope angles in combination with high fibre contents encourage rafting, as is the case at Nein Head 2, Nein Head 3, Langdon Head and West

Grain. Fibres would provide an 'apparent' cohesive quality to the peat mass and restrict the effects of fracture propagation from the shearing layers below during transport.

The generation of slurried peat from the remoulding of basal amorphous layers is also supported by the stratigraphies presented for the North Pennine slides. Amorphous layers may range from thin basal units to thick layers that occupy much of the peat profile depth. The latter might permit greater transport distances as the amorphous layer is worn down, as well as more rapid movement due to lower friction at the base of blocks. The stratigraphic units will vary in significance from site to site, according to slope position and evolutionary history of the peat deposits. For example, peat blanket in which decomposition has been significantly slowed by permanent waterlogging may exhibit a higher proportion of tensile fibrous units, and be more prone to rafting.

The third hypothesis, reflecting the supposed differences between bog bursts and peat slides, is considered in the light of morphological and material evidence described in Chapter 8, and with reference to the peat-substrate profile properties described in this chapter.

In the light of these hypotheses, the failure mechanisms proposed in the published literature may be re-evaluated. Existing hypothesised failure mechanisms were initially examined in Chapter 2, summarised in Table 2.3. Five main mechanisms were listed, the first of which, 'shear failure' referred to the translational failure of peat, substrate or contact along a defined shear plane. All three material layers demonstrate shear failure, and the data described previously is consistent with failure in a plane that corresponds to morphological evidence at slide sites.

The second mechanism, 'buoyancy' referred to hydrologically induced failure, centred upon destabilising pore-water pressures, generated in discrete or diffuse drainage networks at the base of the peat mass or below. While hydrological evidence cited in section 6.2.1.2 suggested the presence of pipes and seepage throughout the peat-substrate profile, a concentration at the peat-substrate interface, or below, was not evident, and pipe sizes were very limited. It is possible that local, very large pipes existed prior to failure at many of the sites, and that discharges through them may have forced separation of the peat blanket from the substrate, but there is little evidence to support this.

Failure by 'lubrication' incorporates alteration in the consistency properties of any of the basal profile materials. Preliminary data suggest that liquid and plastic limits may be locally inconsistent within the substrate. However, remoulding of the sampled units during shearing did not indicate materials 'sensitive' in such a way that failure would initiate through such a progressive change in material properties. Cored samples from the blanket peat surrounding the failure scars did not produce evidence of fluidised materials, although some substrate was soft enough to be sampled. This is rarely achieved in materials of such high clay content.

The remaining initiation mechanisms are based on the restraining characteristics of the upper, tensile peat mass, and of the nature and extent of discontinuities within the remaining peat profiles. Both 'rupture' mechanisms are more usually associated with bog bursts, and require sub-surface swelling to rupture the peat surface, or basal undercutting by fluvial networks to rupture a blanket margin. Most of the peat slides in the North Pennines had neither fluid basal layers, or were in proximity to channels experiencing lateral migration (see Chapter 4).

7 THE RECOVERY AND SIGNIFICANCE OF PEAT LANDSLIDE SCARS

7.0 Introduction

It has been suggested that peat slides are occurring more regularly (section 3.2.2), and hence that their significance in the landscape is increasing. It is unknown whether there are many older slide scars that have revegetated, or recovered completely since failure, and which would alter this interpretation of the temporal distribution of events. Some authors (Tallis, 1985) have suggested that peat slides are responsible for initiating longer term blanket margin drainage systems (Tallis, 1985), which in their subsequent development, rework (or erase) evidence of the original peat slide event. Other authors suggest that peat slides are insignificant erosion features, with minimal long term effects (Radley, 1962). The significance of geomorphological processes acting after failure has yet to be assessed over the medium to long term. This in part reflects the expertise of researchers publishing on landslides, for whom ecological survey is a sideline (Blaschke *et al.*, 2000), and partly the more general difficulty in applying research to the lengthy timescales over which 'recovery' in peat and other landscapes may occur (Flageollet, 1996; Lang *et al.*, 1999; Blaschke *et al.*, 2000). This chapter addresses these issues by relating the period of recovery of peat slide scars to the geomorphological, pedological and ecological processes occurring. The potentially broad scope of such an approach necessitates that the work presented here be regarded as a pilot study of the processes acting on slide scars.

Two key questions relate to peat slide scars in the medium-to-long term. Firstly, do peat slides encourage further degradation through positive feedback mechanisms, e.g. surface erosion and gully extension (Thornes, 1985; Westerberg and Christiansson, 1999)? Or secondly, are they absorbed back into the peat blanket through negative feedback mechanisms, for example, through soil restorative processes determined by the interaction of substrate weathering and vegetation growth (Pandey and Singh 1985; Blaschke *et al.*, 2000)? These ideas form the basis of this chapter.

Investigations into peat slide recovery have been limited in the past (Praeger, 1897; Large, 1991; Feldmeyer-Christe, 1995), considering only geomorphological and ecological approaches, and usually at one site (see Chapter 3). Hypotheses specific to peat slide scar recovery are therefore based largely upon supposition of sequences of recovery derived from other more thorough landslide recovery studies (see section 3.3.3). These are as follows:

i) recovering sites will exhibit distinct spatial patterns and temporal sequences of plant communities with increasing age, and across sites of similar initial conditions;

ii) sites at which recovery is taking place will be characterised by surface mineral conditions that represent a departure from substrate conditions towards more plant hospitable soil (or peat) cover;

iii) sites at which recovery is taking place will be characterised by declining or absent geomorphic activity;

iv) recovery at peat slide sites is more likely to involve a return to a *stable* state, than an approximation of the *original* state, because the climatic conditions under which peat accumulation has occurred no longer exist.

This chapter adopts an integrative geo-ecological approach (e.g. Viles, 1990; Gordon *et al.*, 2001), which assumes that the extent of recovery depends upon the restorative effects of soil development and revegetation on the one hand, and the degrading effects of geomorphic activity on the other. Such an approach is necessarily broad in scope. The research described in the following sections attends to geomorphological, ecological and pedological development in the aftermath of the peat slide event. The availability of a suite of failures of differing age, and under similar climatic, geological and topographic conditions allows the use of a chronosequence approach (Huggett, 1998).

The chapter is divided into three main sections. The first integrates the study of scar geomorphic activity, revegetation, and soil development in a spatially and temporally scaled framework applicable to the North Pennine peat slide population. Appropriate methods are described. The second and third sections present the results of this work and consider the landscape significance of peat slides in the North Pennines, and the wider implications of this work for longer term assessments of peat mass movement activity in moorland areas. The research presented in this and previous chapters is then considered with respect to bog burst features in Chapter 8. The aims of the thesis are reconsidered in the light of previously presented empirical evidence in Chapter 9.

7.1 Methodology

Processes acting on peat slide scars may act at a range of spatial scales. For example, soil development concerns micro-scale alterations in physical structure and chemical composition of the exposed substrate through time. Plant succession primarily concerns macro-scale development of stands of species, as dictated by surface soil and water conditions. The expansion or cessation of geomorphic activity on slide scars is manifest in sediment flux over the full spatial extent of the scar surface. At all scales, within a geo-ecological approach, sedimentary activity, vegetation and soil development are interdependent. Figure 7.1 illustrates a spatially scaled framework for the consideration of peat slide recovery. The spatial scales employed (micro, meso, local and regional) broadly relate to the expected temporal scales of activity. For example, the most important plot scale variations in vegetation and drainage development (as observed in quadrats) will occur over the shortest periods (10^0 a), whilst hillslope variations in vegetation cover and drainage connectivity will be most visible at longer timescales (10^1 - 10^2 a).

The decadal to century timescales of landslide recovery, and the elapsed time between date of failure and investigation preclude the use of direct monitoring approaches at each peat slide site. Landslide scars are often considered as a blank slate (Flaccus, 1959), upon which soil, vegetation and geomorphic processes are re-set. This has stimulated interest in the time required for barren surfaces to be primed for vegetation development, and sequences of landslides of differing age are used to examine this issue through a chronosequence approach. The approach compares the post-failure development of landslides of differing age, but similar form. For example, Flaccus (1959) examined a cluster of translational slide scars spanning 72 years in a tropical environment. He constructed temporally-dependent relationships between soil development and vegetation succession to predict how a future landslide scar might develop post-failure. Back calculations of soil nutrient availability, pH and vegetation extent, based on age-development curves constructed from a test sample, broadly correlated with age for landslides outside the test population. Similar findings were made for other studies in different environments (Pandey and Singh, 1985; Trustrum and DeRose, 1988, Guariguata, 1990). This chronosequence approach is adopted for the study of peat slides in this chapter.

The chronosequence approach is determined by the spatial and temporal availability of sites in the North Pennines. A sequence exists of 14 failures spanning 68 years (comparable to the longest ranges in other cited studies; Flaccus, 1959; Trustrum and DeRose, 1988). All failures occur over similar substrates and under the same climatic regime. Within the small population of peat slides, similarity of scar extent, excavation and slope angle are used as selection criteria. A representative sample of failures is

Figure 7.1. Scaled methodological approach to peat slide scar recovery in the North Pennines

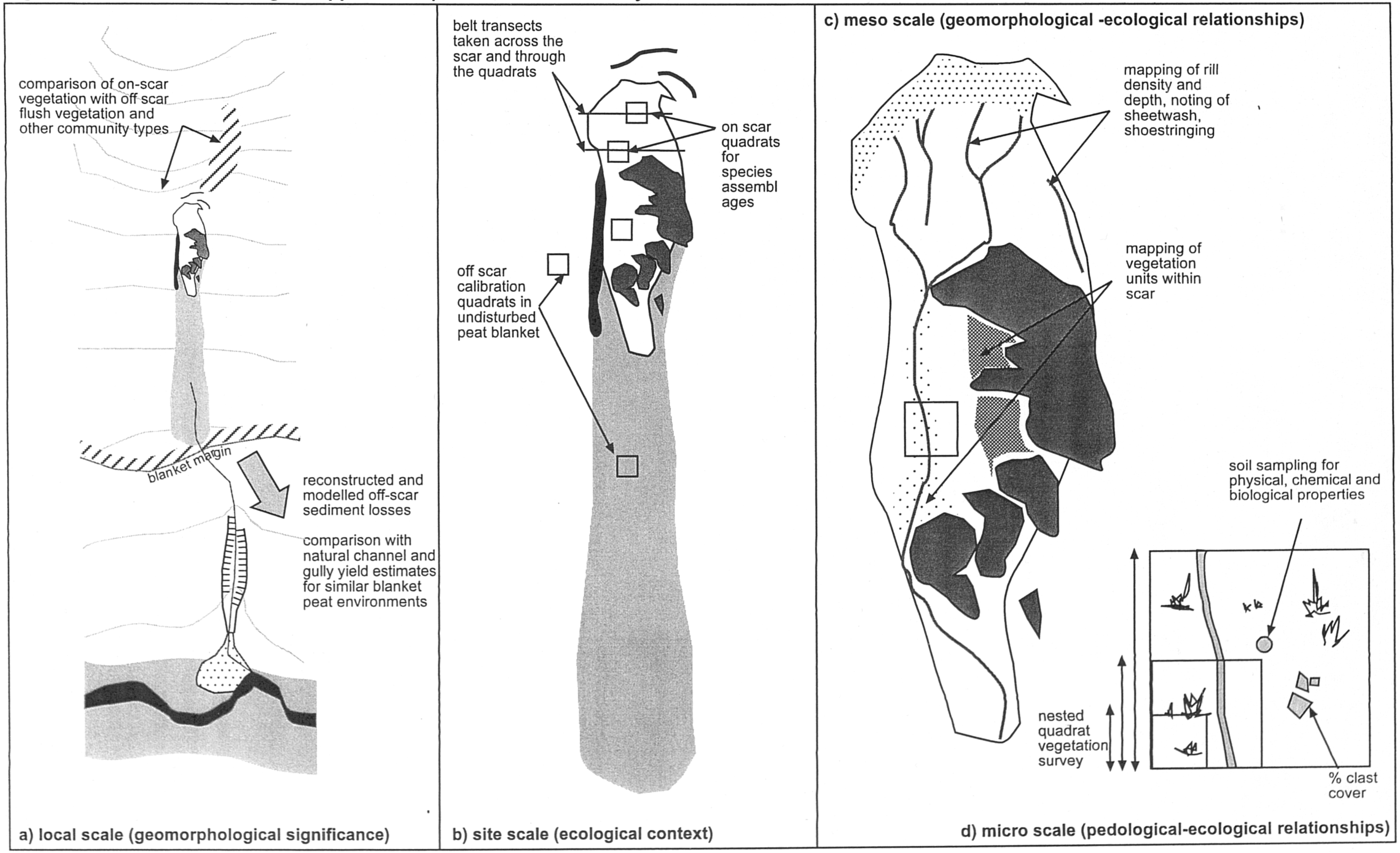


Table 7.1. Peat slide sites studied for recovery characteristics

Site name	Date of failure	Altitude (m.a.s.)	Aspect (deg.)	Catchment	Slope-channel coupling	Volume displaced (m^3)	Degree of scar evacuation	Mean slope angle (deg.)
Dow Crag	06/1930	520	135	Eden	Y	2260	Major	4.0
Meldon Hill East	07/1963	640	45	Teesdale	Y	2110	Complete	13.0
Langdon Beck	??/1961	510	107	Teesdale	Y	1200	Complete	8.0
Iron Band	??/1964	530	270	Eden	Y	14180	Major	10.0
Middlehope	07/1983	550	135	Weardale	Y	2910	Major	10.0
Nein Head 2	07/1983	560	315	Weardale	Y	11600	Major	9.0
Hart Hope	01/1995	540	135	Teesdale	Y	29260	Major	5.7

Table 7.2. Revised Universal Soil Loss Equation factors and significance in controlling soil erosion for peat slide scars.

Factor	Meaning	Control	Inputs
R	Rainfall erosivity (intensity/ duration)/ runoff volume	Extrinsic climatic control on sediment erosion rates	Monthly rainfall totals, annual precipitation totals, mean monthly daytime temperature, no. of freeze free days
K	Soil erodibility	Intrinsic soil structural control on erosion rates	Soil texture, organic matter content, structure, permeability, % rock cover
C	Cover management	Vegetative control on soil surface stability	Root mass/distribution, % canopy cover, canopy height, litter depth
LS	Slope length (L) and slope steepness (S)	Influence of gravity/max. turbulent flow depth	Slope angle and slope length in segments
P	Management practise	None in this simulation	not applicable

Table 7.3. Results matrix for North Pennine recovery study

	Ecological survey			Soil survey		Geomorphological assessment		
Site	Quadrat	Transect	Mapping	Physical	Chemical	R.U.S.L.E.	Reconstruction	Mapping
Benty Hill						Y	Y	
Coldcleugh Head						Y		
Dow Crag	Y	Y	Y	Y	Y	Y	Y	
Feldon Burn						Y	Y	Y
Hart Hope	Y	Y	Y	Y	Y	Y	Y	Y
Iron Band	Y	Y	Y	Y	Y	Y	Y	Y
Langdon Beck	Y	Y		Y		Y	Y	
Langdon Head						Y	Y	Y
Meldon Hill East	Y	Y	Y	Y	Y	Y	Y	
Meldon Hill West						Y	Y	
Middlehope	Y	Y	Y	Y	Y	Y	Y	
Nein Head 2	Y	Y	Y	Y	Y	Y	Y	
Nein Head 3						Y	Y	
West Grain						Y	Y	

used (Table 7.1), spanning most of the age range (1930 to 1995). The sample incorporates proximal failures of differing age at Stainmore and Noon Hill, and a spread of failures of similar age - Middlehope and Nein Head 2 in 1983, and Meldon Hill, Langdon Beck and Iron Band (1961 and 1964) (see Figure 2.15). Middlehope (1983) is selected over Feldon Burn (1990), as it is similar in scar morphology to the other failures. The presence of extensive peaty deposit over the scar area, such as at Feldon Burn, would represent differing baseline conditions for soil development and geomorphic activity. Coldcleugh Head was rejected due to a particularly small scar area, and Benty Hill because of distance from the majority of the slide population, and potentially differing climatic and geological controls in its far westerly location. Nein Head 3, Langdon Head and Meldon Hill West were rejected on the basis of duplication of other sites.

A scaled approach is based around quadrat surveys at the micro-scale, scar surface mapping at the meso-scale, consideration of landform and ecological context at the hillslope scale, and the relative significance of scar geomorphic activity to other catchment-scale processes at the regional scale. The following sections detail the methods used at each scale, by geomorphological, ecological and pedological theme. The aims of the methods described are summarised in a geo-ecological framework for peat slide investigation in section 7.1.4.

7.1.1 Geomorphological activity: post-failure sediment dynamics

Geomorphological activity was considered at each slide scar in terms of the development of scar surface micro-relief by weathering and erosion. In the North Pennines, alteration of the exposed substrate will be primarily by the action of water, and by freeze-thaw activity during the winter months. Reconstruction of sediment loss through mapping of on-scar landforms (rills and gullies) was to have provided a measure of drainage network development across sites of different ages, and estimates of sediment loss through volume measurements derived from rill and gully dimensions. However, the principle intended methods for geomorphic reconstruction at slide sites were only partially completed (for Langdon Head, Feldon Burn and Hart Hope) due to fieldwork restrictions related to Foot and Mouth. While recovery work was undertaken generally in the summer months, the relatively dry scar surfaces made it difficult to assess the true distribution of active drainage lines on the scar, and water sources at the scar margins. Winter surveys, when streamlines were active, would have resolved this problem. As a result of Foot and Mouth, alternate methods for estimating soil losses on a slide-scar scale were adopted using available information.

Within the context of on-scar geomorphological activity, and in the absence of a full array of evidence, it was decided to utilise the Revised Universal Soil Loss Equation (R.U.S.L.E.) to examine variability in potential soil loss controlled by scar surface conditions. Although R.U.S.L.E. has been superseded in recent years by the development of more complex physically based soil loss models (e.g. EUROSEM; Morgan, 1998), it is perhaps the most tested model, and the most understood in terms of its limitations. A further advantage is the (relative) simplicity of its application to soil surfaces for which relatively few physical parameters are required as inputs. Although it was not possible to undertake full geomorphological surveys at the slide sites, some evidence was available which enabled back calculations of yields derived from the reconstructed field evidence of past geomorphic activity. This was compared with the R.U.S.L.E. output.

At the micro-scale (quadrat), surface features were recorded providing evidence of former activity. The presence of surface sealing and crusting was noted, formed by redistribution of fine sediments by the action of raindrops (Stolte *et al.*, 1997). Such surface alteration would block surface pores, impede infiltration, increase bulk density and lower hydraulic conductivity, the net effect being an increased susceptibility to water erosion through enhanced runoff (Singer and Le Bissonnais, 1998; Bajracharya and Lal, 1998). Other features, such as rills, wash lobes and dessication cracking were also noted. Quadrat coverage incorporated top, middle and bottom scar positions in order to account for topographic control over geomorphological processes, and the cumulative effects of drainage activity over increasing slope length. For example, Gabbard *et al.* (1998) noted that sheetwash and rill erosion tend to dominate upper slopes, but with increasing depth and concentration of overland flow in the lower slopes, deeper rilling and gullying take precedence. At the meso-scale (scar), the distribution of the deeper rills and gullies was mapped from both ground survey and analysis of aerial photographs, as these forms were visible even without water. Similar approaches have been adopted by other authors attempting to establish sediment budgets for landslide scars in non-peat areas (e.g. Lundgren, 1978; Pandey and Singh, 1985; Larsen, 1999). Mapped meso-scale landforms included soakways, diffuse lines of drainage, rills, gullies and channels. Rills, gullies and channels may all be used to reconstruct sediment budgets if their age is known (Hudson, 1993; Reid and Dunne, 1996).

Geomorphic information at the micro- and meso-scales was used with soils and vegetation data as input to the R.U.S.L.E and as a basis for reconstruction. The rationale and uses of the two approaches are described below.

The first approach, using R.U.S.L.E., calculates the annual soil loss for slopes using the product of five factors, shown below:

$$A = R \times K \times LS \times C \times P \quad \ldots \qquad \text{Equation 1}$$

where, A equals the soil loss in mass per unit area, R is a measure of rainfall erosivity (dependent on drop size and storm intensity), K is a measure of soil erodibility (based on soil texture, structure and permeability), LS represents the slope length (L) and gradient (S), C is a measure of cropping management (based upon vegetation cover), and P represents management practices designed to prevent erosion. Each factor relates to a quantifiable measure of landform, soil, vegetation, climate and land-use. These factors, their required inputs, and their potential significance in controlling soil erosion on peat slide scars are shown in Table 7.2. Although R.U.S.L.E. is provided with a database to satisfy these parameters, the model is intended for use on agricultural soils in America, and under certain management conditions (Wischmeier *et al.*, 1971; Morgan, 1998). This is clearly not appropriate to the differing environment of UK upland peatlands and landslide scars. However, R.U.S.L.E. provides the capacity to tailor the supporting databases to the environments under study. This option was utilised by entering data specific to the North Pennine environment. Such data included typical rainfall intensities, durations and monthly amounts; vegetation types, stand height and root mass; soil texture, structure and permeability.

R.U.S.L.E. was used to examine variability in predicted soil loss of scar surface material at all sites, using factor data from the chronosequence described previously. Each test run of R.U.S.L.E. was based upon input factors appropriate to the site under investigation. Three sets of scenarios were utilised, reflecting differing objectives. The scenarios were designed to examine contemporary variability in soil loss under differing vegetation cover and soil properties; long term soil loss under changing vegetation cover and soil properties; and hypothetical soil loss under changes in vegetation cover, soil properties or slope angle. The specific details of each scenario are considered with the results of each test run.

The second approach used field evidence at a sub-sample of sites to reconstruct sediment loss. Had further land access been possible, an extension of this work would have formed the main component of geomorphic reconstruction of scar surface activity. The criteria for reconstruction were based on the following premises:

i) Erosion will occur where the scar surface is unvegetated;

ii) Total erosion will reflect the relative contributions of sheet, rill, interrill and gully erosion across the scar (and wind erosion, not quantified here);

iii) Positive changes in vegetation cover will occur at the expense of sediment yields from erosion.

Ultimately, the total erosion over the scar surface could be represented in the following relationships:

$$a_e = a_r + a_i + a_s + a_g \quad \ldots \quad \text{Equation 2}$$

$$v_e = v_r + v_i + v_s + v_g \quad \ldots \quad \text{Equation 3}$$

$$v_l = v_e - v_{st} \quad \ldots \quad \text{Equation 4}$$

where:

a_e	is the total scar area under erosion in m^2
a_r	is the area experiencing rill erosion in m^2
a_i	is the area under interrill erosion in m^2
a_s	is the area under sheet erosion in m^2
$a_{g:}$	is the area under gully erosion in m^2

In many cases, these areas could be calculated from aerial photographic evidence, or two-dimensional field maps (e.g. Figure 7.1c). The variables prefixed 'v' refer to volumetric measures of the same processes, with units in m^3. Changes in drainage density with age were evaluated by establishing drainage densities (network length divided by scar area) for each slide scar at a known number of years after failure. This provided the area under rilling, a_r, and gullying, a_g, in extreme cases. The remaining unvegetated areas were those susceptible to interrill, a_i, and sheet erosion, a_{sh}, processes, which transport material to rills and gullies, whereafter it is removed or remains in storage.

Volumes of material displaced through each erosion process were estimated with knowledge of mean rill and gully depth and total depth of degradation by sheet and interrill erosion. The use of clast exposure at slide sites where scars had previously been bare (determined through time-lapsed ground photography) allowed a coarse estimate of the surface lowering. Equation 4 represents the reconstructed sediment yield, and may be directly compared with the R.U.S.L.E. output for each scar.

Revegetation rates were determined using field mapping combined with scar areas measured from aerial photographs. Simulated revegetation was applied as increasing percentages of cover of the slide scar, to the detriment of eroding scar area. As percentage vegetation cover increased, it did so at the expense of the most geomorphologically stable areas. Areas were 'revegetated' in the following order: sheet, interrill, rill and gully eroding areas.

To complement the 'event' phase sediment budgets calculated in Chapter 5, sediment yields from the scar surface processes were grouped under the collective banner of the 'surface modification' phase. In addition to both the 'event' and 'surface modification' phases, a third phase was added, referred to as the 'deposit breakdown' phase.

The 'deposit breakdown' phase allows for the breakdown of slurried deposit. Site visits demonstrate that slurry does not exist at peat slides in excess of 5 years in age (such as Hart Hope), though it is still present at sites under two years in age (e.g. Coldcleugh Head, Figure 4.20). Little is known of the processes and rates that act to remove this deposit, though slurry seems to be a common feature of most, if not all recorded slides. The geomorphological maps in Chapter 4 suggested that slurried areas were usually delimited by the outer limit of blocky deposit at each site, and on this basis, the area subject to slurrying within these confines was estimated.

The degree to which slurry volumes reflect basal, fluidised peat, or rapidly remoulded and broken blocky deposit is uncertain. However, slurry volumes cannot exceed the total volumes excavated less the block and raft deposits recorded. On this basis, it was possible to calculate tentative slurry volumes. A time limit of 5 years was applied for the full breakdown of slurry by natural processes, using the absence of slurry at Hart Hope to set the upper limit. On this basis, rates of sediment loss derived from slurry breakdown could be estimated.

At the local scale, geomorphological recovery would require a return to conditions approximating those prior to failure, be it active drainage or otherwise. To investigate this, aerial photographs were analysed for evidence of prior geomorphic activity and compared with the current status of each slide scar. Connecting systems both upslope (e.g. flushlines) and downslope (e.g. gullies) were mapped. This was attempted for the Noon Hill slides, and at Feldon Burn and Hart Hope. Geomorphological changes to coupled stream networks caused by the effects of sediment supply from the scar surfaces, and channel modification by event deposit inundation were not considered within this thesis. In the case of the latter, this is because most modifications will be short term and in the immediate aftermath of failure.

At the regional scale, sedimentary significance of peat slides may be considered in terms of the 'event' phase, the 'deposit breakdown' phase and the 'surface modification' phase. The products of these phases may be compared with the major agent of sediment delivery in the North Pennines, fluvial activity. Estimating sediment volumes derived from peat slides, relative to sediment yields from the wider blanket peat landscape, enable a judgement to be made as to the significance of peat landsliding.

The catchment provides a convenient landscape unit for assessment of sediment budgets at the regional level. The catchment scale is appropriate in that nearly all material exported from a catchment (except aeolian transport) passes from valley sides and valley floors in the major river channels. Spatial clustering by catchment may also be examined at this scale, e.g. the significance of the 1983 Noon Hill slides in the context of Weardale and Teesdale geomorphological activity.

Crisp (1966) produced estimates of sediment losses from a small blanket peat catchment in the Moor House reserve. Data was collected during a one year monitoring period (October 1962-October 1963). Crisp's sediment yield, attributed primarily to bank erosion, was 93 t km^2 a^{-1} for the catchment in question. Evans and Warburton (2001) summarise other subsequent research in blanket peat areas of the South Pennines, where yields are less, at 50 t km^2 a^{-1} (Labadz *et al.*, 1991). Their own suggested yields for the North Pennines are closer to 32 t km^2 a^{-1} (Evans and Warburton, 2001). This value incorporates both mineral and organic sediments derived from failed bank material and wash. The three values suggest that yields may have declined since Crisp's (1966) original study. Extrapolating these values produces an annual decline in yield at a rate of approximately 3800 t a^{-1}.

7.1.2 Ecological activity: plant colonisation and succession

Vegetation was studied primarily at the micro- and meso-scales. At the micro-scale this was by quadrat, with a size appropriate to the moss, herb, shrub and grass layers that characterise peat blanket areas. A system of nested quadrats was employed to enable discrimination of the evenness of species distribution (Sakai and Ohsawa, 1993). These were of 0.25 m^2, 1.0 m^2 and 4.0 m^2 sizes (Figure 7.1d). Previous studies (Douglas and Trustrum, 1986; Lambert *et al.*, 1993; Rodwell, 1991) and more general recommendations for research into herb and shrub communities specify sizes within, but not greater than this range (Shimwell, 1972). Quadrats were placed within the scar from top to bottom, and at calibration points outside the scar on the blanket surface, to determine the vegetative conditions characteristic of species assemblages proximal to the former peat surface.

Cover abundance of plant species may be measured as frequency or density (Greig-Smith, 1957). The use of frequency requires the discrimination of individual plants within the quadrat, which while easily applicable to thick stands of reed, or to trees and bushes, is less easy to apply to the continuous mats of vegetation found in peat bogs. Because comparison between intact and disturbed ground is required, a density approach was used instead. Percentage amounts of each species were estimated in the field for each quadrat size, by measuring x and y dimensions of distinct species stands, and summing of their totals. In some cases, species grew in mixed mats, and these were measured as mixed units, and then separated equally by the number of species in the unit during analysis. It was decided in the first instance not to apply the simpler Braun-Blanquet cover abundance scale (Braun-Blanquet, 1951; Shimwell, 1972), or alternatives, as these can be derived from percentage values in the aftermath of measurement. All vegetation surveys (described here and below) were undertaken between July and August 2000. Plant species were identified according to descriptions in Phillips (1994), with vascular species described according to species lists published in Environmental Change Network protocols for standard measurements at terrestrial sites (Sykes and Lane, 1993).

At the meso-scale, vegetation transects (or releves) were taken across the slide scars, incorporating the quadrats, and perpendicular to the downslope scar axis (Large, 1991; Figure 7.1b). Presence/absence of species was recorded along the line of the transect over the scar and to just beyond each scar edge. The presence and absence of stones and clay (or peat in floes), and the presence of rills and drainage lines were also noted. Transects were not undertaken at Meldon Hill or Dow Crag, due to land access problems. In contrast with similar transects undertaken in other forms of ecological survey (such as contemporary species variations in intertidal zones), altitudinal variations were not considered important. Vegetation stands were mapped in the field using base maps of enlarged aerial photographs, and according to common assemblages of vegetation. Vegetation units corresponding to each common assemblage were defined using these field recordings.

At the local (hillslope) scale, there exists a considerable diversity and 'patchiness' to vegetation distribution in moorland areas (Lewis, 1904), in part a product of local variations in hydrological properties and relative relief. As a result, wide-ranging vegetation mapping would be required in order to provide representative species associations against which to compare on-site conditions. Equally, the total removal of vegetation types during slope failure, and likely changes in deposit-top vegetation conditions make it difficult to say with any certainty what the composition of recovering vegetation should approximate. One way of addressing this is through the use of aerial photographs showing pre-existing site conditions, and using existing published work about vegetation associations to infer the likely disturbed communities. Therefore, the same pre-failure aerial photographs used to map geomorphological conditions were also used to infer ecological landscape components.

Ecological change at the regional scale is not considered, because it is unlikely that patch level changes in vegetation species will impact the development of species outside the immediate locality of the slide scars, unless the former peat areas are the only habitat for particularly rare species types.

7.1.3 Pedological activity: substrate physical and chemical alteration

Soil properties are usually examined in profile with depth, or through spatial changes in surface characteristics. In the case of peat slide scars, preliminary investigations suggest that exposed substrate does not exhibit significant soil cover. However, it is possible through analysis of substrate samples to determine to what extent substrate exposed to subaerial processes has altered from the unexposed substrate beneath. Such physical and chemical alterations may benefit vegetation growth or alternatively may encourage erosion through the formation of crusts.

A single cylindrical soil sample was extracted from bare ground within each quadrat (Figure 7.1d). As a result, these samples included surface particle distributions likely to be associated with micro-scale geomorphic processes (wash and splash). Soil chemical qualities would also be most closely associated with subaerial weathering of the substrate material, rather than a temporary product of nutrient cycling between plant and 'soil'. The soil samples were taken in non-reactive plastic tubes, of 4 cm diameter and 20 cm in depth, with a minimum soil depth extracted of 10 cm. This is consistent with sample sizes and depths used in other studies (e.g. Flaccus, 1959; Lundgren, 1978; Westerberg and Christiansson, 1999).

Soil properties were examined as follows. The soil samples were extruded in the laboratory, and then split longitudinally (Baize, 1993). Basic stratigraphic logs of structure and horizons were made (Hodgson, 1976), and to remain consistent with the previous chapter, Troels-Smith (1955) classifications were also employed for each unit and supplemented with the modified von Post scheme (Hobbs, 1986).

The top and bottom 2 cm of each sample were removed and then subdivided for physical and chemical analyses. This represented the minimum possible size across samples to satisfy all tests to be conducted. Where the bottom 2 cm appeared to be different in origin from the rest of the sample, additional supplementary samples were taken from the middle 2 cm of the sample. Furthermore, supplementary samples were taken on four of the sites to establish if progressive changes with depth were visible. Control samples were taken at the Hart Hope site from the substrate of cores extending beneath the undisturbed peat blanket to the scar margins. These provided substrate material which had not been exposed to subaerial weathering, erosion or biological processes, and hence a measure of whether scar surface properties differed significantly from those of buried substrate.

Particle size analysis was undertaken by laser diffraction using a Coulter™ Laser Particle Granulometer. Hydrogen ion activity (or pH) was conducted on soil solutions made up of 10 g of soil in 25 ml of distilled water, according to methods described in Rowell (1994). Exchangeable Magnesium (Mg^{2+}), Sodium (Na^{+}), Calcium (Ca^{2+}) and Potassium (K^{+}) were derived by leaching 5g of each soil sample with ammonium acetate, and then igniting the leachate in an atomic absorption spectrophotometer (Rowell, 1994). Cation exchange capacities (C.E.C.) were derived for the same samples, using the Markham apparatus, after rinsing of the same samples with ethanol, and then further leaching with sodium chloride solution. Organic matter content was established by burning at 850°C for 30 minutes, as described in Ball (1964). Test runs for carbonates using HCl effervescence were negative, as one would expect with acid soils, and carbonate testing was not undertaken (Zarin and Johnson, 1995).

Soil development was not examined at the site scale, as the quadrat samples provided a limited at-a-point assessment of variations in soil formation downslope, and soil development was neither sufficient nor variable enough to justify mapping. However, the presence of rafts, and blocks as both sediment sources and bare surfaces for revegetation (or floes) were recorded.

At a local scale, reference levels for peat depth against which recovery could be gauged were obtained from the cores described in Chapter 6. In addition, supplementary cores were taken across and down-scar at the oldest of available sites, Dow Crag (1930), to investigate if surface vegetation found there related to sub-surface development of peaty soil. Soil development was not examined at the regional scale.

The rationale for the three strands of methodology employed at slide scars may be better understood when integrated in a geo-ecological framework. Data provided through each method provides a summary of the balance between destabilising geomorphic activity and stabilising vegetation growth. Soil physical and chemical processes may tip the balance in favour of either, depending on whether development encourages erosion or colonisation. While the methods presented here are subdivided by academic discipline for clarity, they are integrated at the four scales - micro-, meso-, local and regional for the description of results, as it is the combination of their activity that controls the extent of recovery. For example, micro-scale processes may indicate priming of the substrate for vegetation development, not visible at the meso-scale, nor manifest at the local scale.

7.2 Results

Geomorphological, ecological and pedological data were collected for seven of the fourteen North Pennine sites, as shown in Table 7.3. Integration of the data sources, reflecting the balance between substrate degradation by drainage development and stabilisation by vegetation, was modelled using the R.U.S.L.E. and the reconstructive sediment budgets for all sites. Result are described by landscape scale, and in a temporal sequence from the youngest scars to the oldest, reflecting the progressive changes in scar surface processes occurring over time. The site-scale recovery maps (Figures 7.2a to f) provide site-wide information on drainage development and vegetation, as well as detailing the positions of quadrats and sections. They are described fully in section 7.2.2.

Figure 7.2 a. Hart Hope recovery map

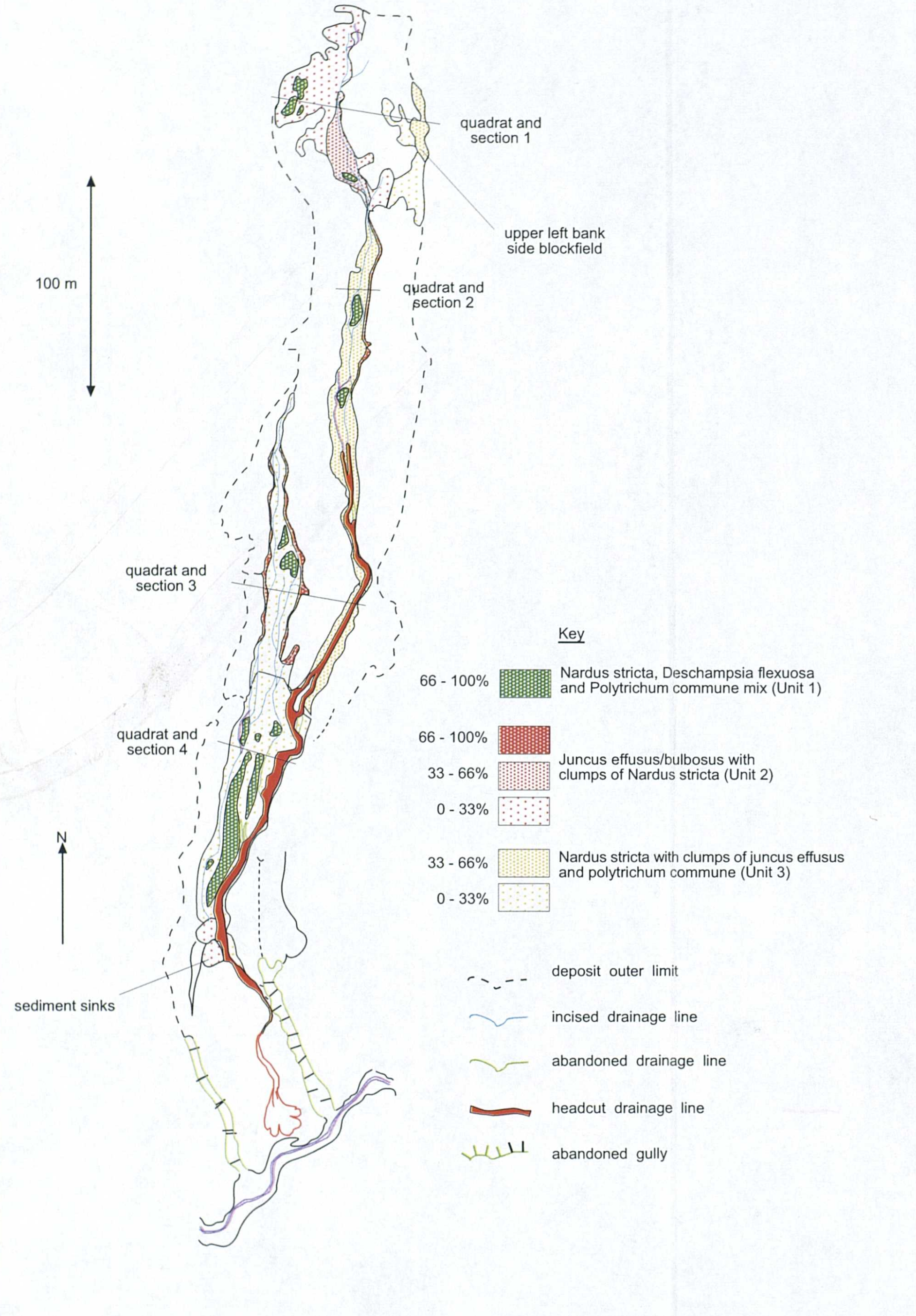


Figure 7.2 b. Nein Head 2 recovery map

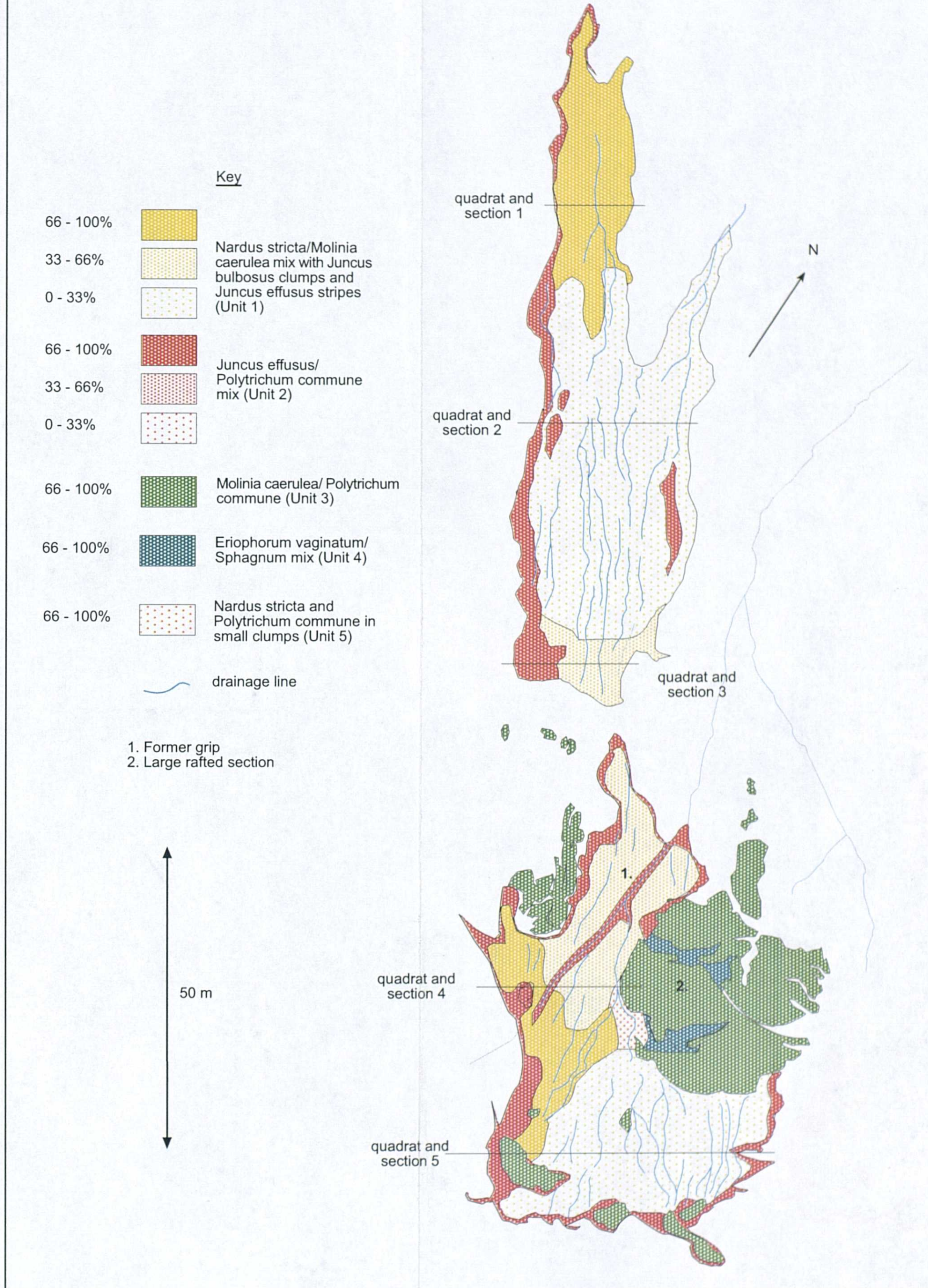


Figure 7.2 c. Middlehope recovery map

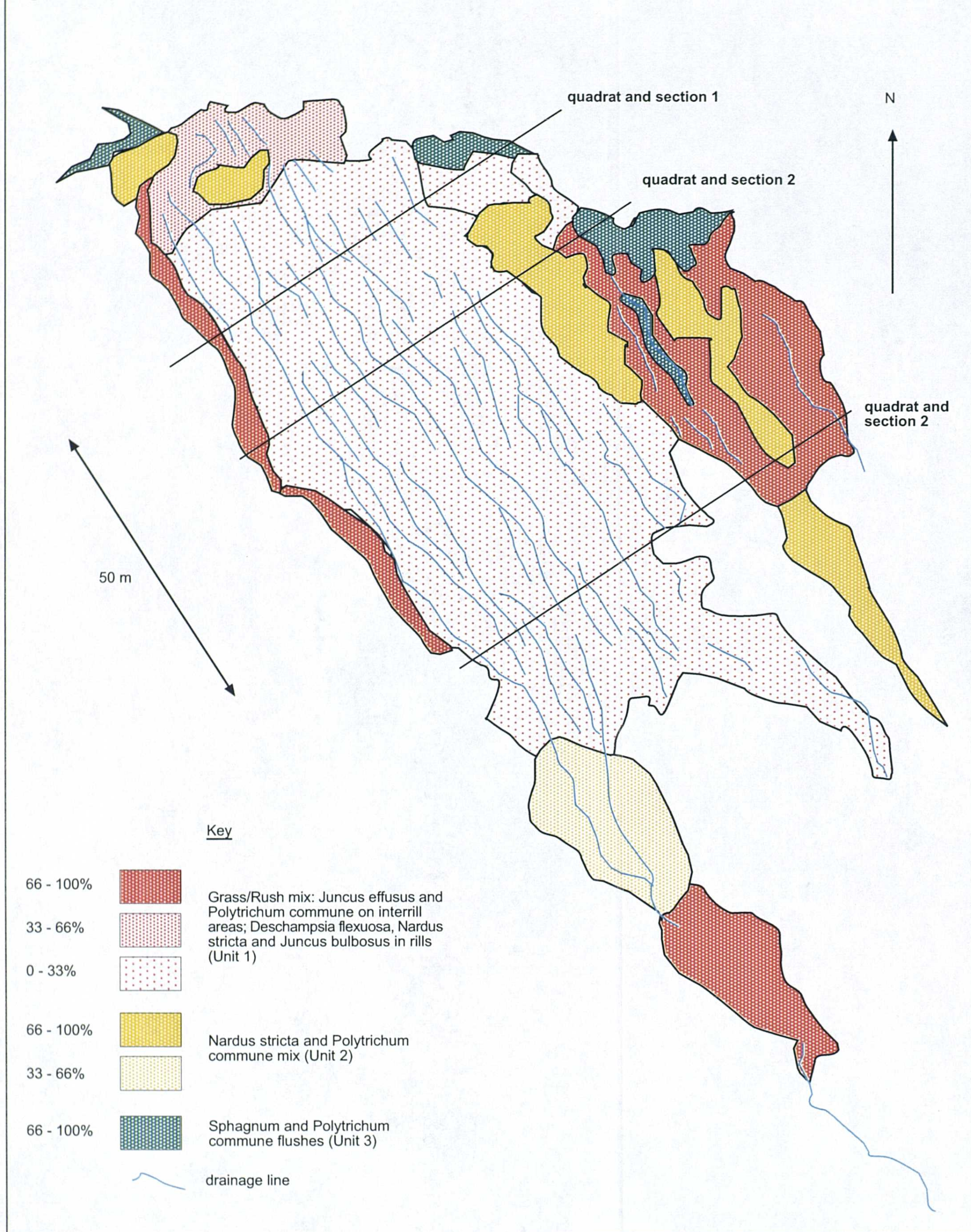


Figure 7.2d. Iron Band recovery map

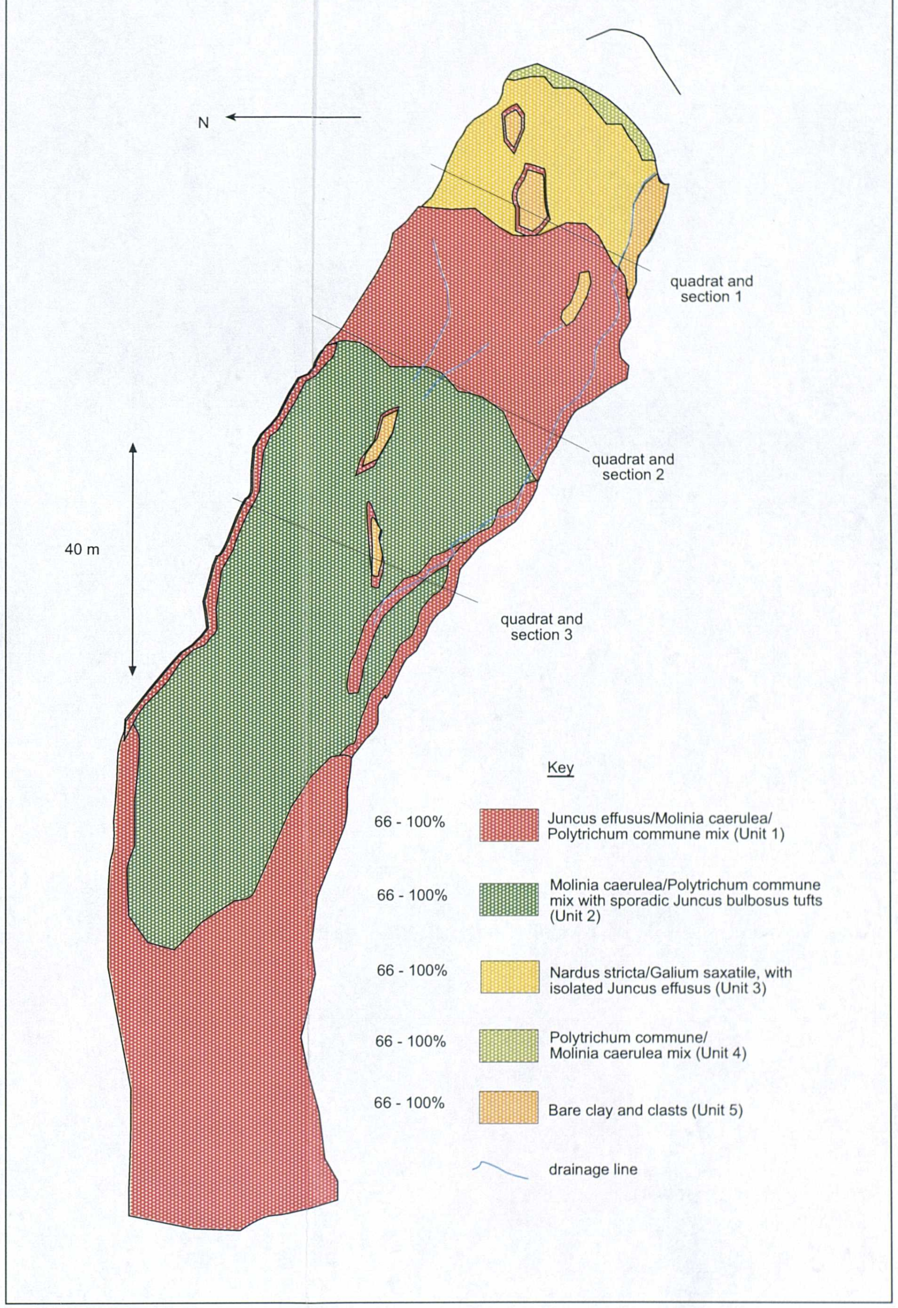


Figure 7.2 e. Meldon Hill East recovery map

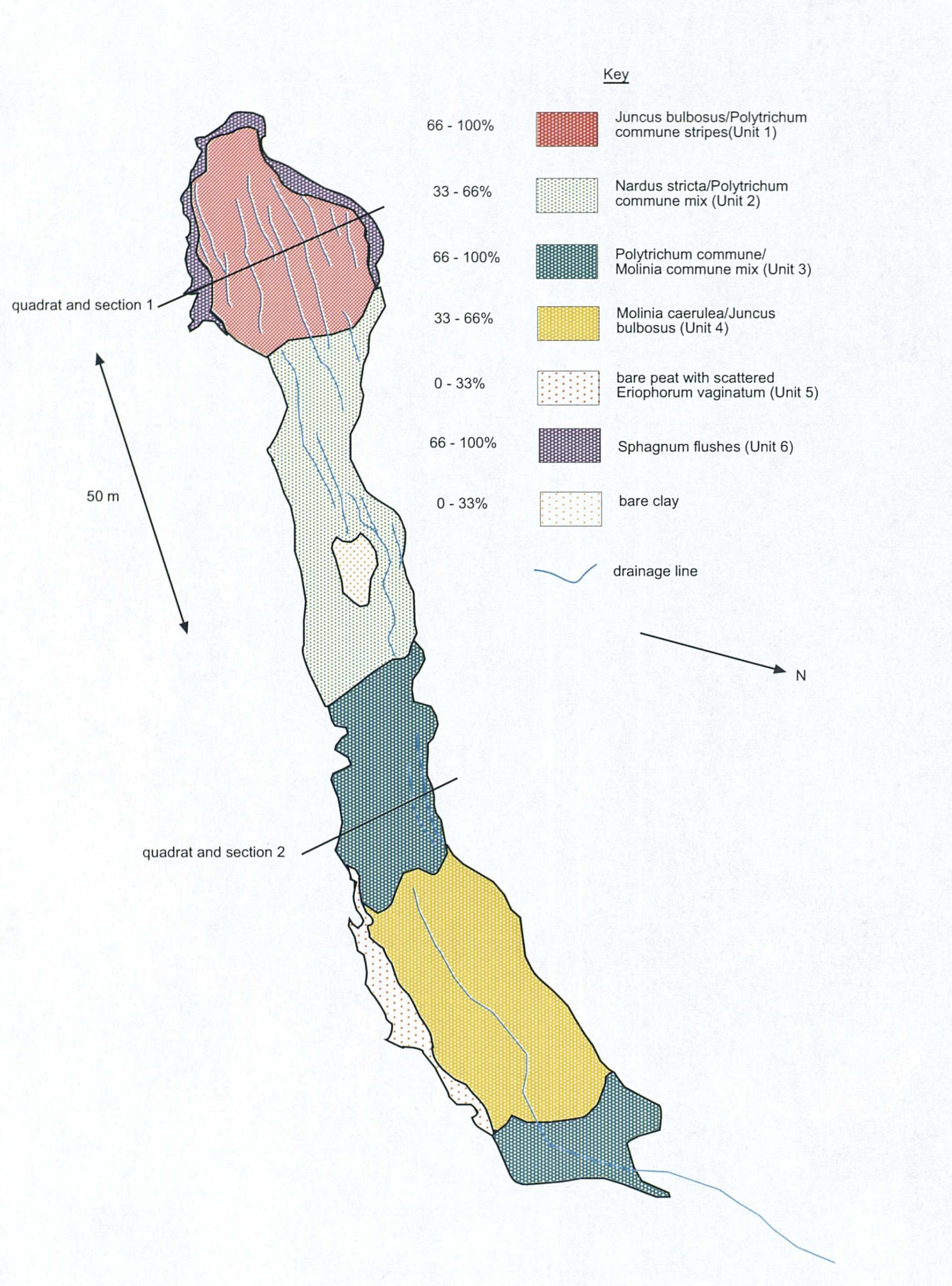
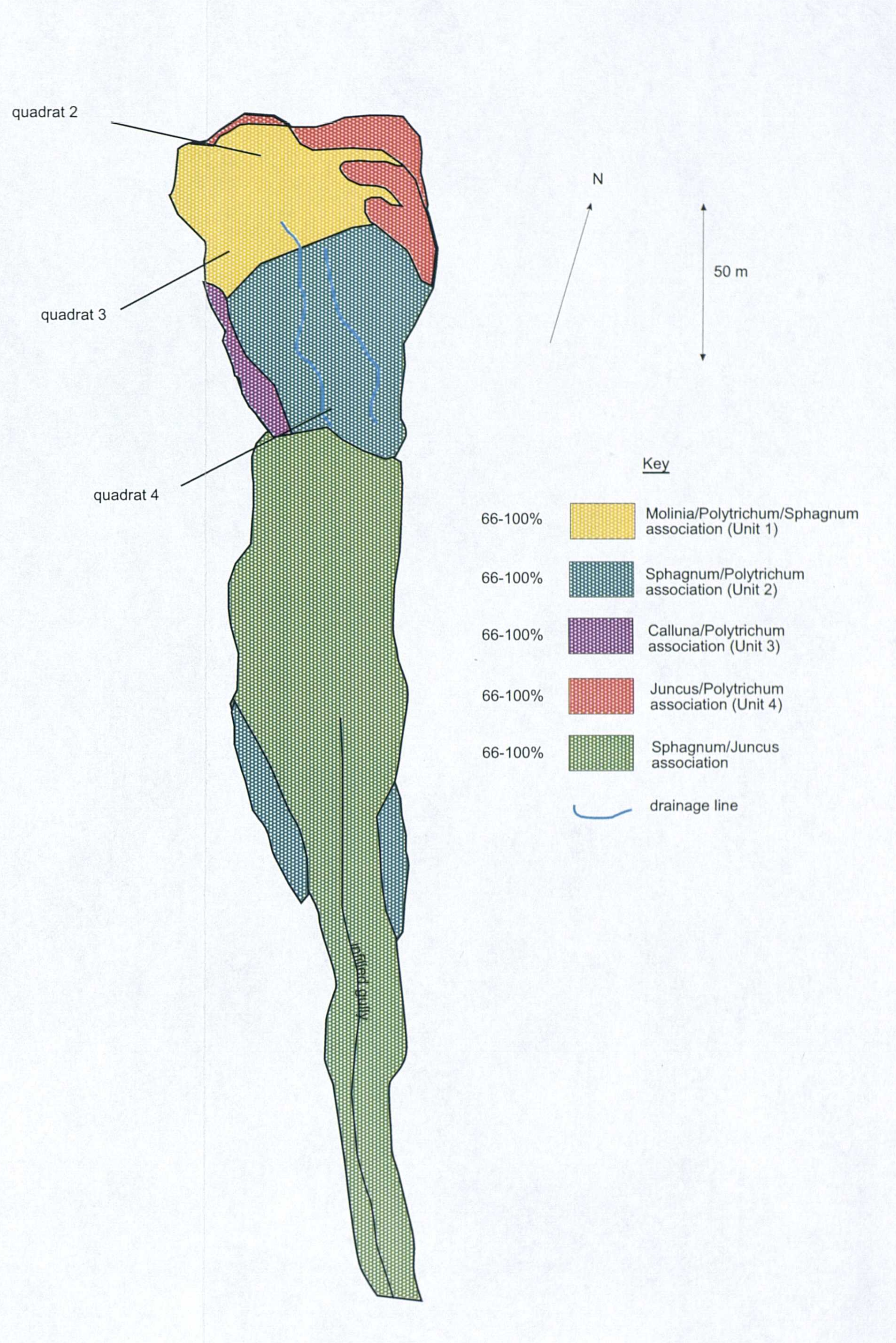


Figure 7.2 f. Dow Crag recovery map



7.2.1 The micro-scale: plot scale variability in vegetation development, sedimentary characteristics and soil physical and chemical properties

Information at the micro-scale is held primarily within the quadrats taken across the seven peat slide sites. Quadrat (and transect) locations are shown on the recovery maps. In most cases, individual species could be clearly discriminated within each quadrat, and their extent and density measured accordingly. In some cases, a layered coverage existed (such as a *Molinia caerulea* tufts within a *Sphagnum* base layer), and a joint class was used in density estimation. For presentation, mixed communities are separated according to the number of species in the class, and all figures henceforth refer to single species densities only.

Figures 7.3a to e show the vegetation data as percentage column charts for each on-scar quadrat. Moving from left to right in each chart, the columns represent the 0.25 m^2, 1.0 m^2 and 4.0 m^2 levels of nesting. A similar distribution of vegetation across the three levels of nesting denotes homogeneity of coverage within the quadrat limits (e.g. Dow Crag, Quadrat 2), whilst highly variable percentages illustrate patchiness (e.g. Meldon Hill East, Quadrat 1).

On the slide scars themselves, there is a general trend towards increasing vegetation coverage with increasing age. Mean percentages of quadrat total coverage for each site are plotted against scar age on Figure 7.4, and illustrate a strong linear relationship (r^2: 0.92). However, the plot also suggests that scars are already revegetated to 15% coverage immediately after failure. Photographic evidence presented shortly, and common sense, suggest this is not the case. It is likely that revegetation is non-linear, and that the early period of revegetation (0 - 10 years) is characterised by initially very slow, but increasingly rapid colonisation. The rushes and grasses shown in the quadrats at young sites may act as nursery plants for the mosses and flowering species (e.g. *Galium* spp., *Polytrichum* spp.), or prime the substrate surface through initiation of nutrient cycling and loosening of surface structure.

Species in evidence across sites fell into three main genera, rushes, grasses and mosses, with some localised flowering species (Table 7.4). The percentages shown in Table 7.4 indicate an increase in moss species relative to grasses with age of site, and a decline in the amount of bare ground. The presence of rushes and grasses is highly variable across all sites. The composition of quadrats at each site will now be considered, from the most recently exposed scar (Hart Hope), to the oldest (Dow Crag). Photographs of quadrats at Hart Hope, Nein Head 2, Iron Band and Dow Crag

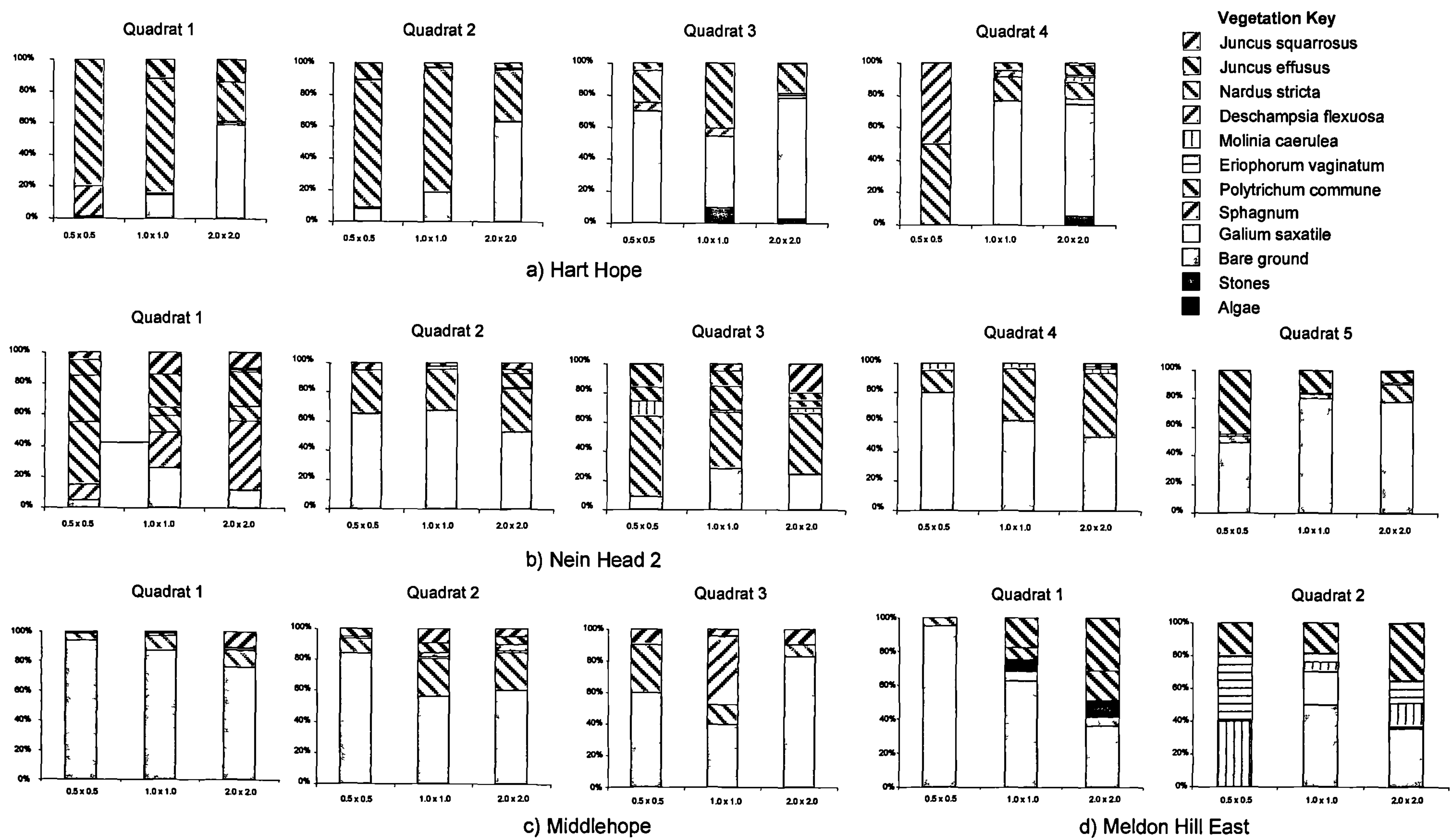


Figure 7.3. On-scar quadrats for Hart Hope, Nein Head 2, Middlehope and Meldon Hill East

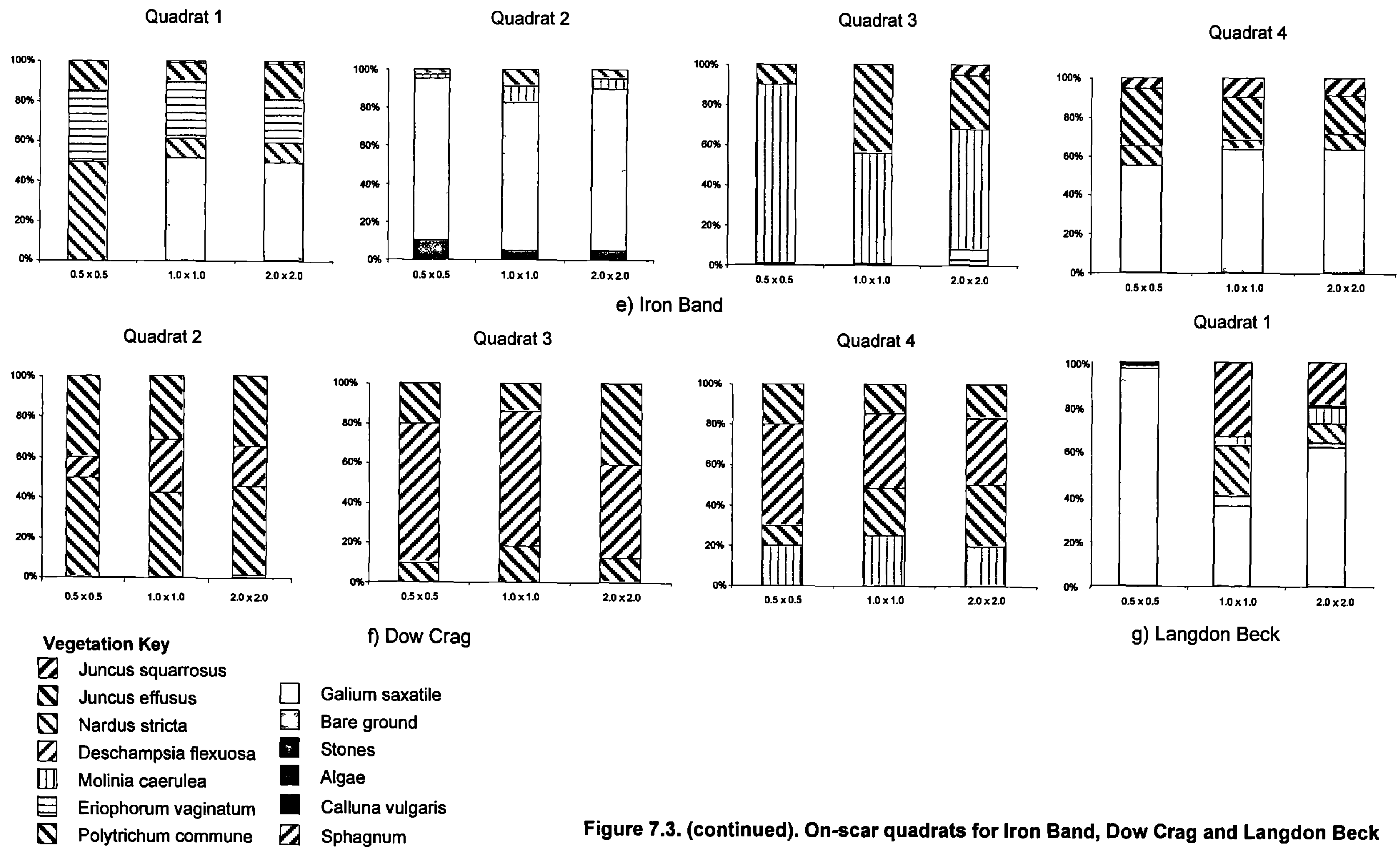


Figure 7.3. (continued). On-scar quadrats for Iron Band, Dow Crag and Langdon Beck

Figure 7.4. Change in percentage vegetation cover with age (%)

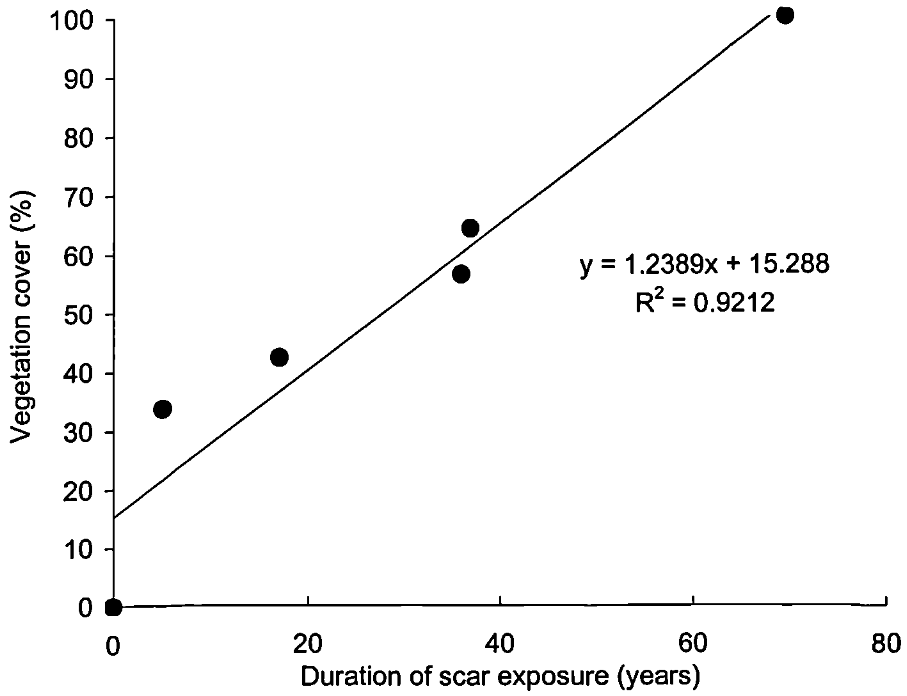


Table 7.4. Percentage grass, rush, moss and other species across all slide sites

	Mean cover for all quadrats (%)			
Site name	Grasses	Rushes	Mosses	Other
Hart Hope	22.8	6.9	0.3	1.8
Nein Head 2	34.3	10.6	7.4	0.0
Middlehope	17.0	8.0	1.8	0.0
Langdon Beck	45.0	20.0	5.0	5.0
Meldon Hill East	17.5	16.5	26.0	0.5
Iron Band	43.8	15.5	22.9	1.5
Dow Crag	4.9	33.7	61.4	0.0

Figure 7.5. Photographs of on-scar quadrats at four peat slide sites of increasing age. a) channelised section below upper scar at Hart Hope (1995), 38% percentage vegetation cover, *Nardus* and *Juncus*; b) rill incision at Middlehope (1983), 35% vegetation cover, predominantly *Nardus*, *Juncus* and some *Polytrichum*; c) *Polytrichum* more established on quadrat right hand side at Iron Band (1964), 42% vegetation cover, mainly *Juncus*, *Polytrichum* and *Nardus*; d) complete revegetation at Dow Crag (1930), 100% vegetation cover, mainly *Polytrichum*, some *Juncus*, some *Sphagnum*. All photographs taken in July/August 2000.

are shown in Figure 7.5.

1. **Hart Hope (1995):** on-scar quadrats are characterised by patchiness, particularly in quadrats 1 and 4, with overall coverage ranging between 25% and 40%. Grass species (most probably *Nardus stricta)* dominate the vegetated patches, with small stands of rushes (*Juncus effusus* and *Juncus squarrosus* together to 6% on average) making up most of the remainder. A slight increase in the number of species is observed downslope, including the presence of flowering *Galium saxatile*, and the introduction of *Deschampsia flexuosa* and *Molinia caerulea.*

Off scar quadrats located above the head and adjacent to the scar toe, suggest a heath grassland dominated by *Molinia* with extensive *Nardus* (60% - 70% together). This supports an underlayer of moss species, primarily *Polytrichum commune* (4%) and some degraded *Sphagnum*, in which *Galium* may also be found in significant quantities (33%).

2. **Nein Head 2 and Middlehope (1983):** both scars exhibit considerable variation in cover both within and between each site. Nein Head 2 has the greater overall coverage (57% to 27%), and more range (20% - 90% to 18% - 40%). Unsurprisingly, this within-site variability is also reflected in high patchiness within the quadrats of Nein Head 2, and moderate patchiness at Middlehope.

Again *Nardus* dominates at Nein Head 2 (12% - 40%), with *Molinia* (2% - 8%) also present. Rushes exist in greater quantities than at Hart Hope, with both *Juncus effusus* and *Juncus squarrosus* present to 24% in places, the latter the dominant of the two. Moss growth has initiated at some locations, with *Polytrichum commune* ranging between 2% and 20%. At Middlehope, *Nardus* is greatest in quantity, with more consistent *Juncus squarrosus*, and smaller quantities of *Molinia*, *Deschampsia* and *Polytrichum.*

The off-site quadrats are quite different, with a *Nardus/Molinia* association at Nein Head 2 (supported by both *Sphagnum* and *Polytrichum*), while Middlehope displays a wide range of rushes, sedges (including *Carex echinata*), grasses and mosses. Species diversity is greater over the peat surrounding Middlehope, and this is also reflected in greater on-scar diversity in species type.

3. **Iron Band (1964), Meldon Hill East (1963), Langdon Beck (1961):** variability between these sites is somewhat greater than described previously, possibly as a consequence of their distribution across the study region. Iron Band is characterised by

high percentage cover (75%) but also by high patchiness. Meldon Hill East is less revegetated (64%) and equally patchy, while Langdon Beck is relatively unvegetated (37%) with moderate patchiness. Langdon Beck is a particularly small scar, and may experience differing sequences of revegetation.

At Iron Band, *Molinia* and *Nardus* make up the grass cover, with isolated introduction of *Eriophorum vaginatum* (Quadrat 1). *Polytrichum* is present to greater amounts than described previously (17% - 27%) and *Juncus squarrosus* may also be found. Calibration quadrats suggest a full blanket cover characterised by *Molinia*, *Juncus squarrosus* and *Polytrichum commune*.

Diversity of species type is greater at Meldon Hill, with algae, flowering species, rushes, mosses and grasses present across the two on-scar quadrats. This is the first site to have exhibited *Sphagnum* on the scar. The calibration quadrat suggests an undisturbed blanket dominated by grasses and mosses (including *Sphagnum*) and localised clusters of *Galium*.

Langdon Beck also exhibits flowering species, rushes, grasses and mosses, though no *Sphagnum*. *Juncus squarrosus* dominates (19%), with *Nardus* and *Molinia* providing similar coverage together. The calibration quadrat indicates an undisturbed association of *Calluna vulgaris* and *Molinia caerulea*. Mosses and grasses are also found.

4. **Dow Crag (1930):** the 33 year gap in age between the 1960's failures and Dow Crag sees vegetation coverage rise to 100% across all on-scar quadrats. There is considerable regularity in species associations and little patchiness within and between quadrats. Mosses and rushes provide nearly all the vegetation, and *Sphagnum* ranges between a considerable 20% and 50%. *Juncus effusus* and to a lesser extent *Juncus squarrosus* provide canopy cover, with *Polytrichum commune* also found in large quantities (12% - 45%). Species diversity is low. The surrounding peat blanket exhibits a strong association of *Eriophorum vaginatum* and *Calluna vulgaris.* Species diversity is also low.

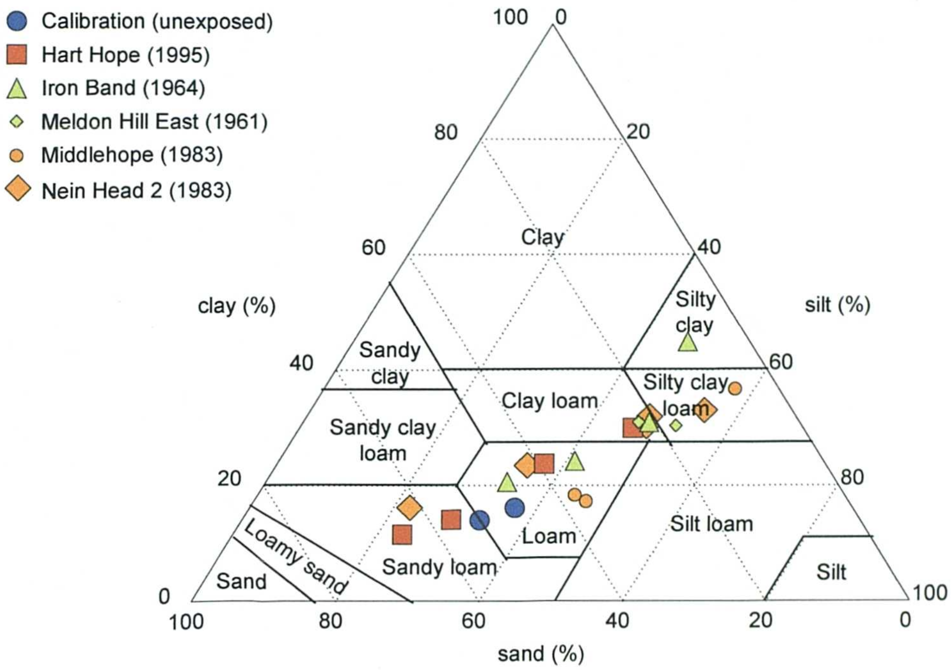
Assessment of micro-scale geomorphological processes focused on comparison of surface grain-size distributions from top to bottom of each slide scar, and between scars of different ages. Grain-size distributions were used to examine if exposed substrate had changed significantly in particle-size distribution from unexposed substrate beneath. Changes might indicate modification by subaerial weathering and erosion. Variations were also examined in down-scar distribution of grain-size, to examine whether altitudinal sorting or sorting by slope distance had occurred by surface wash processes. Observation of micro-relief, such as wash lobes, shoestringing and crusting, supplemented the analysis of particle size distributions.

Figures 7.6a and b show ternary grain size plots for the main recovery sites. Sub-samples from the bottom of each soil sample are shown plotted for texture in Figure 7.6a, and separated by site. The United States Department of Agriculture (U.S.D.A.) texture classes are shown to provide a textural context for each sample. The U.S.D.A. system is used because R.U.S.L.E., as an American model, requires U.S.D.A. textural classes as inputs. The major difference between the U.S.D.A. system and the UK system is that all samples falling above 20% clay content in the latter are incorporated in the clay loam sized fraction or finer. On a site-by-site basis, textures range between sandy loams and silty clays, with a slight tendency for the older sites (Iron Band and Meldon Hill East) to cluster in the finer fractions. The Hart Hope substrates and calibration samples from beneath the peat blanket are scattered throughout the sandy loam to clay loam texture classes. Given that all samples are 10 cm or more below the ground surface, they are not expected to show any grain-size variations other than those which are site-specific. Figure 7.6b shows the top samples from each site. Here, clustering is more pronounced, with all of the Hart Hope samples designated as sandy loams or loams, and all of the older samples as loams, silt loams or silty clay loams. The range of sand-sized particles is relatively consistent across the bottom and top samples, but there is an increase in the silt fraction. This may represent increased formation of micro-aggregates with increased subaerial exposure and weathering. If this is the case, there may be a weathering front, manifest in consistent grain-size changes with depth (the pedogenic hypothesis). Alternatively, there may be a sorting effect, where the coarser, less cohesive sand and silt-sized fractions are entrained and washed from the surface material with increasing effectiveness downslope (the geomorphic hypothesis).

Figure 7.7a tests the pedogenic-weathering hypothesis. The four samples for which micro-profiles of grain size were taken are plotted against soil core position. Hart Hope, Nein Head 2 and Iron Band quadrat 4 demonstrate increased clay content with depth, and increased clay content with site-age. Iron Band quadrat 6 is anomalous, and causes difficulty in the acceptance of pedogenic weathering as a consistent control of grain-size distribution with depth. Attempts to relate changes in clay fraction to slope position showed no clear relationship, refuting the geomorphic hypothesis.

Figure 7.7b illustrates the significance of clay content in cracking on drying. The photographs show substrate samples after wetting, mixing and air drying. Samples

a) bottom samples.



b) top samples

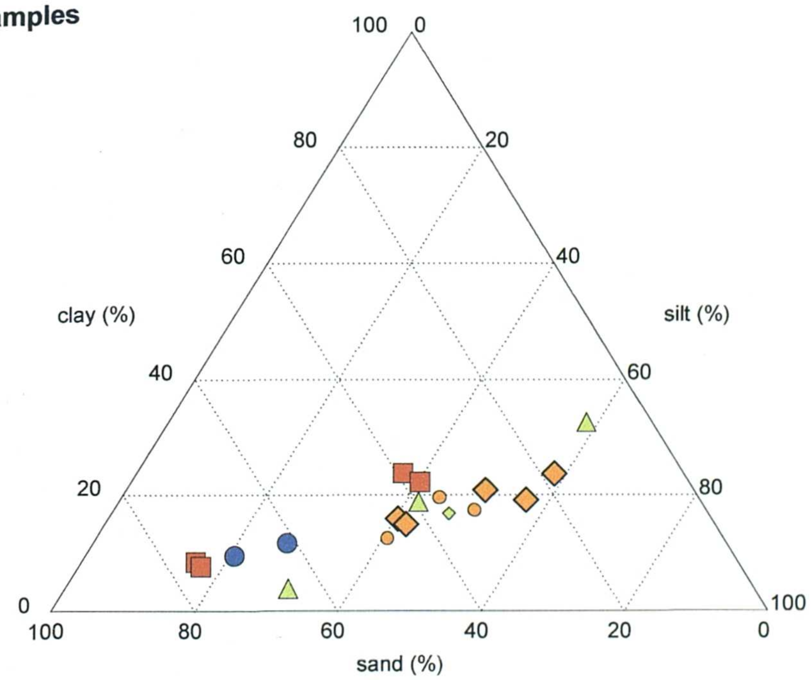
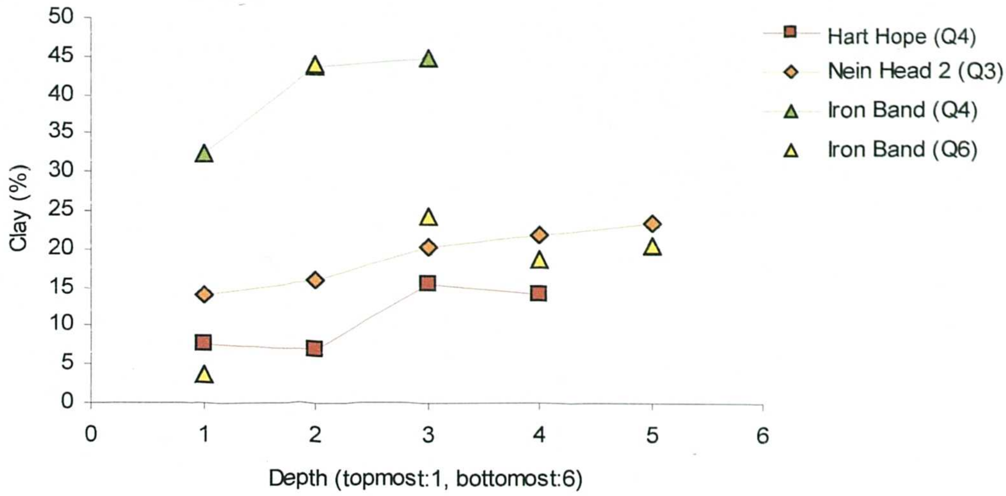
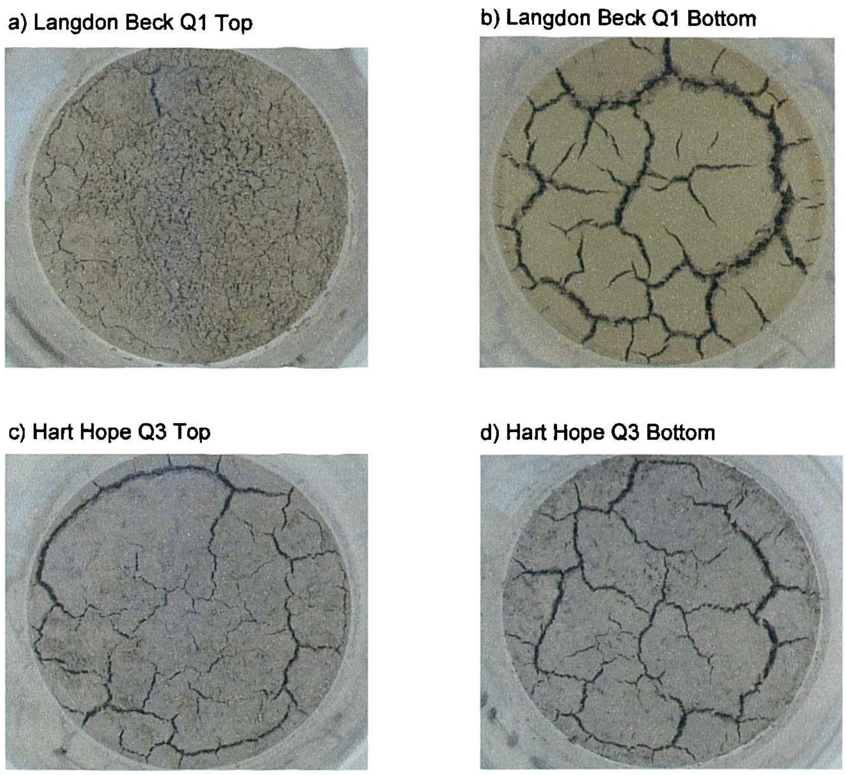


Figure 7.6. Ternary plots of texture for a) bottom samples and b) top samples, by quadrat for each site.

Figure 7.7a. Variation in percentage clay content with depth for the four subsampled soil columns



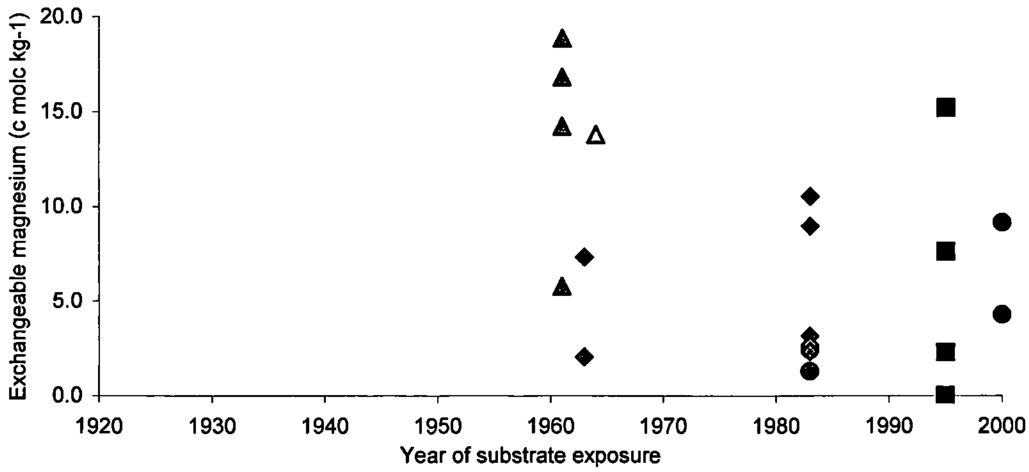


	Clay (%)	Silt (%)	Sand (%)
Langdon Beck Top	6.3	21.2	72.5
Langdon Beck Bottom	24.6	43.2	32.2
Hart Hope Top	22.1	40.4	37.5
Hart Hope Bottom	23.7	37.2	39.1

Figure 7.7b. Dessication cracking as a function of grain size for Langdon Beck and Hart Hope.

Figure 7.8a. Soil pH for quadrat top samples at all sites.

b. Exchangeable magnesium (Mg^{2+}) for quadrat top samples at all sites.



c. Exchangeable magnesium (Mg^{2+}) for quadrat bottom samples at all sites.

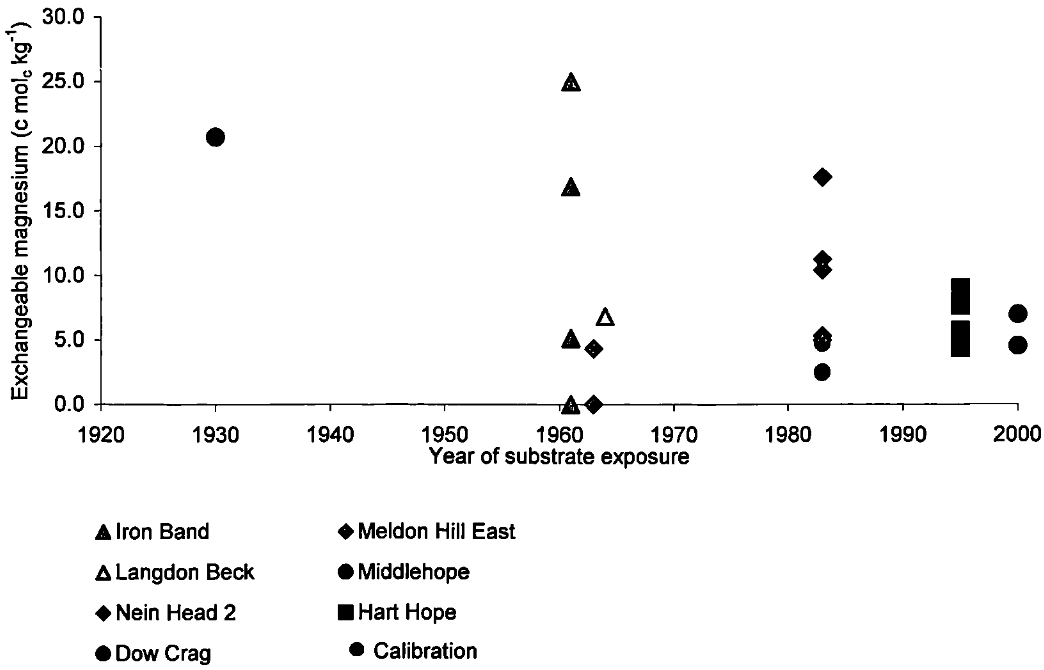


Table 7.5. Summary statistics for cumulative grain size distributions by site and sample

Sample set	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Variance (μm)	Skewness	Kurtosis
Hart Hope (top)	50.5	98.6	269.2	8.4	71.2	-0.604	-0.692
Hart Hope (bottom)	37.5	43.9	269.2	10.0	100.7	-0.244	-1.021
Nein Head 2 (top)	22.5	24.2	153.8	6.4	40.4	-0.304	-0.387
Nein Head 2 (bottom)	22.9	24.0	168.8	7.2	52.2	-0.235	-0.66
Middlehope (top)	25.8	36.5	116.3	5.9	34.2	-0.559	-0.292
Middlehope (bottom)	15.4	16.8	105.9	6.1	37.2	-0.218	-0.642
Iron Band (top)	21.9	24.4	127.6	7.2	51.4	-0.223	-0.582
Iron Band (bottom)	13.2	12.8	153.8	7.5	55.7	-0.035	-0.93
Meldon Hill East (top)	24.4	34.3	96.4	5.9	34.4	-0.551	-0.129
Meldon Hill East (bottom)	11.5	11.2	5.9	7.0	49.1	0.051	-0.69
Langdon Beck (top)	152.1	225.9	993.5	7.5	55.4	-0.981	0.398
Langdon Beck (bottom)	19.0	16.8	153.8	8.5	72.9	0.021	-0.815
Hart Hope (calibr. top)	85.2	196.7	324.3	7.6	57.5	-0.954	-0.059
Hart Hope (calibr. bottom)	49.3	62.9	295.5	9	81.5	-0.366	-0.811
All sites (top scar)	25.3	31.2	140.1	6.7	45.4	-0.364	-0.528
All sites (mid scar)	25.8	25.1	185.3	8.3	69.7	-0.187	-0.846
All sites (bottom scar)	39.5	50.6	140.1	6.9	47.4	-0.485	-0.297

Table 7.6. Presence /absence of key soil surface physical processes at scar quadrat sites

			Quadrat survey			Stratigraphic logs		
Sample	Site name	Scar location (1:top; 5:bottom)	Washing /rilling	Sealing/ crusting	Cracking	Washed layers	Pan formation	In situ weathering
HHQ1	Hart Hope	1				✓		
HHQ2	Hart Hope	2	✓	✓	✓	✓		
HHQ3	Hart Hope	3		✓	✓	✓		
HHQ4	Hart Hope	4	✓	✓	✓	✓	✓	
NH2Q1	Nein Head 2	5			✓			
NH2Q2	Nein Head 2	4	✓		✓			✓
NH2Q3	Nein Head 2	3	✓		✓			✓
NH2Q4	Nein Head 2	2	✓	✓	✓			✓
NH2Q5	Nein Head 2	1	✓	✓	✓			
MidQ1	Middlehope	1	✓	✓	✓	✓	✓	✓
MidQ2	Middlehope	2			✓			
MidQ3	Middlehope	3	✓		✓			✓
QHQ1	Langdon Beck	3		✓	✓			✓
S1964Q3	Iron Band	1				✓		
S1964Q4	Iron Band	2		✓	✓	✓		✓
S1964Q5	Iron Band	3						✓
S1964Q6	Iron Band	4	✓	✓	✓	✓		✓
MelEQ1	Meldon Hill E	1	✓	✓				✓
MelEQ2	Meldon Hill E	2	✓	✓				✓
S1930Q1	Dow Crag	1	n/a	n/a	n/a			
S1930Q2	Dow Crag	2	n/a	n/a	n/a			
S1930Q3	Dow Crag	3	n/a	n/a	n/a			
S1930Q4	Dow Crag	4	n/a	n/a	n/a			

which exhibit more clay content at depth (such as Langdon Beck, LB Q1 T and LB Q1 B, and Hart Hope), display pronounced cracking in the newly formed clay layer. Sample homogeneity, such as in Hart Hope Quadrat 3 yields little variation in cracking between the top and bottom samples. Table 7.5 gives a statistical summary of grain size information.

Field observation of micro-scale landforms correspond with the laboratory investigations of grain size. Three significant soil surface processes were noted, namely cracking, sealing/crusting and soil loss by water erosion. Presence or absence of each process is shown in Table 7.6. Apart from the vegetated quadrats, in which the soil surface was obscured, sealing and crusting of the soil surface represented the most common form (14 of 23 sites), with cracking and washing occurring at 11 of 23 sites. There was little temporal or spatial pattern to the occurrence of processes, although the 1960's sites appeared to show less wash than the more recent sites.

Stratigraphic logs substantiate some of the comments above. Key features within each sample are noted in the final three columns of Table 7.6. Washed layers refer to distinct horizontal layers of particle fractions that appear foreign to the material above and below in the sample units. Pan formation refers to hard layers, which are often coloured and appear to be a product of downwashing and leaching of minerals, rather than inwashing from further upslope. Clastic fragments that are visibly disintegrating in situ are noted in the 'in situ weathering' column.

Soil chemical properties were evaluated for all on-scar samples with the intention of identifying temporal changes in nutrient availability, soil surface acidity and incorporation of organic matter into the mineral substrate. Baseline conditions at peat slide sites should initially be highly unreceptive to vegetation colonisation. An inhospitable substrate surface would be manifest by acid and base poor conditions, with a mineral substrate with minimal organic matter. Heavy texture and waterlogging would also impede aeration and limit the activity of flora and fauna.

Four main sets of tests were undertaken. Soil pH, exchangeable cations, base saturation and organic matter content were analysed for top and bottom samples of scar material for all of the sites except Dow Crag. At this site, the surface consisted almost entirely of peaty material grading into very wet and compressible *Sphagnum* leaf and stem structures. For this site, only exchangeable cations, base saturation and pH were derived. Results are considered with each soil sample separated into top and bottom sub-samples. If soil forming activity has initiated at any site, differences between top and bottom samples should be visible for each parameter.

On the whole, values collected for the sites of differing age illustrate increasing variability in pH, organic matter content and nutrient content/availability. However, within site variability is frequently as great as between site variability, and the extrapolation of weak trends reveals little. A brief summary of chemical properties follows. A representative selection of plots is shown in Figure 7.8.

Soil acidity, represented by pH, is shown in Figure 7.8a for quadrat topsoil samples. There is a slight trend towards declining acidity with increasing duration of scar exposure in the top samples (pH ranges from 3.5 to 5.5), while most pH values are scattered between pH 4 and pH 5 in the bottom samples. Dow Crag exhibits more acid conditions, and as surveys described subsequently suggest, it is the only site to have developed a significant species cover indicative of bog forming conditions. Such vegetation may signify a return to pre-failure soil characteristics, in terms of acidity at least.

Figures 7.8b and c show plots of top and bottom sample exchangeable magnesium for all sites. Figure 7.8b mirrors the results for the other exchangeable cations, with the presence of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} independent of scar age. Values for all mineral nutrients range between 0.24 c mol_c kg^{-1} for K^{+} at Hart Hope, and 20.72 c mol_c kg^{-1} of Ca^{2+} at Dow Crag. The calibration samples taken from beneath the peat blanket at Hart Hope also fall within these ranges. The values are realistic for the texture classes and percentage clay content exhibited by the soils (Rowell, 1994). The top samples (e.g. Figure 7.8b) show a slight tendency (e.g. Mg^{2+}: r^2: 0.21) for increasing variability in mineral nutrients with age, but again variability within sites is almost as great as that between sites. Base saturation, as expected, parallels the quantities of mineral nutrients. While there is increased scatter with age in the top samples, there is little clear distinction in availability between sites on the basis of age.

Organic matter contents are generally low (0% - 12%) in the bottom samples and cannot be separated by age across the sample population. The top samples illustrate greater variability, particularly at Hart Hope and at the 1960's failures, and organic matter contents reach up to 85%. The Hart Hope result may be a function of the 'humic black soil' comprising the top of the sample, while variability in fibre content may explain the other results.

Soil physical properties were considered through stratigraphic logs of each sample, and supplemented the textural analysis of the previous section. A variety of structural aggregates was found across the sample set. For example, at Hart Hope, the soil surface samples were characterised by granular silty surface horizons, which appeared to have resulted from wash, and beneath which lay sandy clay. At Nein Head 2, the uppermost units consisted of dark grey platy clay, with local fibres. Beneath this stiff and aggregated material were found more brittle and sandy units. The local sandy nodules in these samples appeared to be the in-situ weathering products of former sandstone clasts. Samples from Iron Band varied significantly in structure, with no discernible pattern with either depth or scar location. Units included dark grey clays with sandy nodules and fine fibres, to lighter and stickier amorphous clays. At both Langdon Beck and Meldon Hill, substrate samples appeared to become less sandy with depth, into stiffer clays with weathering clast fragments. The Dow Crag sample appeared peaty, with samples taken anywhere other than the upper scar area consisting of a very wet, grey detrital mud. This range of units, from loosely structured and presumably low bulk density surface samples to stiffer and heavy textured substrate at depth may influence drainage and available rooting depth, and hence control revegetation rates. The relationships between soil physical and chemical properties are considered further in the light of vegetation data in section 7.4.

7.2.2 The meso-scale: site scale patterns of revegetation

Two approaches were undertaken in mapping vegetation composition at each peat slide slide-scar. Broad-scale on-scar vegetation maps were supplemented with higher resolution presence/absence transects, taken at a series of locations down-scar. The vegetation maps are a key component of the recovery maps (Figures 7.2a to f) and a description follows.

Figures 7.2a to f show the vegetation distributions for each of the slide sites. Initial observations indicate that Hart Hope and Nein Head 2 are more complex in vegetation composition than the other slides, and this may partly be a function of the scales of the features in the field. Although Malmer and Regnell (1986) recommend a minimum unit area for vegetation map units of 400 m^2, this would be an inappropriately large area given the size of some of the slide scars, and their morphological complexity. Vegetation units shown on the maps are based upon stand observation in the field, and hence are of unit sizes appropriate to the species under study.

Figure 7.2a illustrates vegetation zonation at Hart Hope. Three main species associations (or units) occur on the site. The most widely distributed unit is a predominantly *Nardus stricta* cover type (Unit 1). Clumps of *Juncus effusus* and *Polytrichum commune* are pocked at random within this broader *Nardus* mat. Coverage is greater in the central channelised scar section and within the upper left blockfield (33% - 66%), and lower in the right hand side lower scar (0% - 33%). The uppermost scar area is dominated by the second unit (Unit 2) of *Juncus effusus* and *Juncus bulbosus* with pockets of *Nardus* (0% - 33%). This unit is also found over two sedimentary sinks where the lower scar pinches out prior to gullying. Where the scar constricts into its confluence with the left hand side blockfield, coverage increases to 33% - 66%. Thin bands along the scar edges of the central channelised section and the lower right bank scar also show extensive *Juncus*. Remnant peat deposits (blocks and floes) are mantled by nearly 100% coverage of *Nardus*, *Deschampsia flexuosa* and a *Polytrichum* understorey (Unit 3).

Nein Head 2 (Figure 7.2b) is dominated by a primary unit (Unit 1) of *Nardus* and *Molinia* with *Juncus bulbosus* clumps and *Juncus effusus* stripes. Coverage is variable, from 0% - 33% in the upper flatter scar areas of both scars, and thicker (33% - 100%) in the lower scar areas. The *Juncus effusus* stripes tend to follow drainage lines, particularly rills, and a good example of this can be seen in the diagonal band that follows the former grip in the upper scar zone. Most drainage lines are too narrow to be adequately represented at the scale of the vegetation map. Where *Juncus effusus* becomes dominant, and in conjunction with *Polytrichum* it is represented as a second unit (Unit 2). In addition to its presence along drainage lines, this unit is found frequently around the scar margins. Blocks, floes and the large rafted section in the upper scar are covered in Unit 3, a *Molinia/Polytrichum* association, while wet pools found in large tears between rafts are currently infilling with Unit 4, an *Eriophorum vaginatum/Sphagnum* association. A small sub-unit (5) of *Nardus* and *Polytrichum* is found in the middle of the upper scar.

Although of the same age, Middlehope (Figure 7.2c) is represented by a complex mixture of rushes (*Juncus effusus* and *bulbosus*) and grasses (*Deschampsia, Molinia* and *Nardus*), such that no characteristic species based unit can be derived (Unit 1). Coverage ranges between 0% - 33% in the main scar area, to 66% - 100% at the scar margins, toe and in the left bank side blockfield. The second, more uniform unit (Unit 2) is comprised primarily of *Nardus*, with mixed *Juncus* spp., and occurs most prominently over both blocks and floes and within the left hand side blockfield. Pronounced wet flushes across much of the scar head are characterised by the third unit (3) of *Sphagnum* and *Polytrichum*.

Coverage is greater and complexity much less so at each of the 1960's failures, and at Dow Crag. Iron Band (Figure 7.2d) and Meldon Hill (Figure 7.2e) both exhibit segmented zonation of units downslope with coverage between 66% and 100% for all units. At the latter, *Polytrichum* forms an understorey to *Juncus squarrosus* in the upper scar (Unit 1), to *Nardus* in the middle scar (Unit 2), and with *Molinia* (Unit 3) above and below the oversteepened and rilled *Molinia/Juncus* lower scar (Unit 4). Bare peat with scattered *Eriophorum* comprises the fifth unit (5) on the lower right bank side, while at the top of the slide, a sixth unit of *Sphagnum* dominated flushes is found (Unit 6). At Iron Band, a *Juncus squarrosus/Molinia/Polytrichum* association (Unit 1) occupies much of the middle and lower scar and margins, and with a significant decline in *Juncus,* comprises Unit 2 in the remainder of the middle scar. The third unit (3) is made up of *Nardus* and *Galium*, with some *Juncus* clumps and occupies the upper scar, across the top of which is a thin *Polytrichum* and *Molinia* band (Unit 4). There are noticeable bare clay patches surrounded by mainly mixed rushes and grasses in the upper and middle scar areas.

Finally, at Dow Crag (Figure 7.2f) complexity is further reduced, and all coverage is at 100%. The scar is dominated in its upper, steeper plane by a *Molinia/Polytrichum/ Sphagnum* association (Unit 1), and in its lower flatter portion by a *Molinia* deficient *Sphagnum/Polytrichum* unit (Unit 2). The scar periphery is bordered on the lower right bank side by *Calluna vulgaris* and *Polytrichum* (Unit 3), and in the upper torn and rafted region by *Juncus* and *Polytrichum* (Unit 4). What appears to be an infilled former gully is occupied by extensive rushes and mosses.

The vegetation transects are useful in elucidating fine-scale detail from each of the maps, and description of three examples follows. At Hart Hope, bare scar areas compare with rich associations of vegetation across blockfields and at the scar margins. Flowering species occur in combination with grasses across block tops, and small clumps of rushes and weeds pock the scar surface. Mosses are found only in conjunction with rushes, and species diversity increases downslope. At Nein Head 2, there is greater cover abundance, mainly apparent in the long, unbroken stands of grasses. Species diversity increases again with distance downslope, with more rushes and flowers. Moss species are found in greater abundance than at Hart Hope, but frequently without being associated with rush species. At Iron Band, there is similar cover to Nein Head 2, but a greater abundance of mosses and rushes in association. Flowering species are found at the scar margins more regularly, but less so in the scar centre. The transects at Middlehope and Langdon Beck display similar patterns, but with highly fragmentary *Juncus* patches across-scar at Middlehope.

7.2.3 The meso scale: observation, simulation and reconstruction of scar geomorphic activity

Geomorphological processes at the scar scale reflect the erodibility of the soil and the extent to which it is protected by vegetation cover. Soil physical attributes and vegetation extent have been considered in the previous sections. Their effects, as simulated in the R.U.S.L.E. and through reconstruction are described in this section. However, prior to the use of modelling and reconstruction, field mapping of on-scar fluvial activity was undertaken at three of the slide sites. At Feldon Burn (1990) and Langdon Head (1983), the presence of rills, channels, zones of diffuse drainage and the location of point inputs at the scar margin were mapped. A similar approach was undertaken at Hart Hope (1995), but previous work examining channel headcut recession using monumented sections, was added to with a second set of measurements. Drainage development maps and summary statistics for channel features are presented accordingly. It is not proposed to examine in detail here the mechanisms of headcutting noted at Hart Hope, as such activity has not been recorded to a similar extent elsewhere. However, it should be noted that the presence of headcutting at Hart Hope is significant in geomorphic terms, and the absence of evidence of headcutting at other sites does not necessarily preclude its occurrence in years prior to the surveys described here.

Figure 7.9 shows maps of drainage development at Langdon Head (1983) and Hart Hope (1995). The grey shaded areas represent the (predominantly) bare scar surfaces at both sites, whilst the red sections denote headcut drainage lines. Assuming an absence of significant drainage lines in the immediate aftermath of failure (see Figures 7.10a and b for examples), the rill and channel patterns evident at both sites must have formed in the period since.

At Hart Hope, scar width narrows beneath the upper scar, and drainage originating in this area is concentrated in a relatively small region between large masses of disturbed peat. This concentration of discharge appears to have allowed aggressive upslope headcutting of a major channel on the left bank scar (Figure 7.10c), which has propagated for at least half the distance of the total failure. The current channel discharges sediment onto a fan over a pronounced break of slope at the foot of the slide (Figure 7.10d). Abandoned gullies to either side of the active fan suggest that the channel is prone to rapid migration in its lower sections. This is demonstrated by the presence of several cut-off features in the lower-middle scar area. Sedimentation is clearly visible in the right hand side gully (Figure 7.9).

Figure 7.9. a) Hart Hope and b) Langdon Head drainage maps

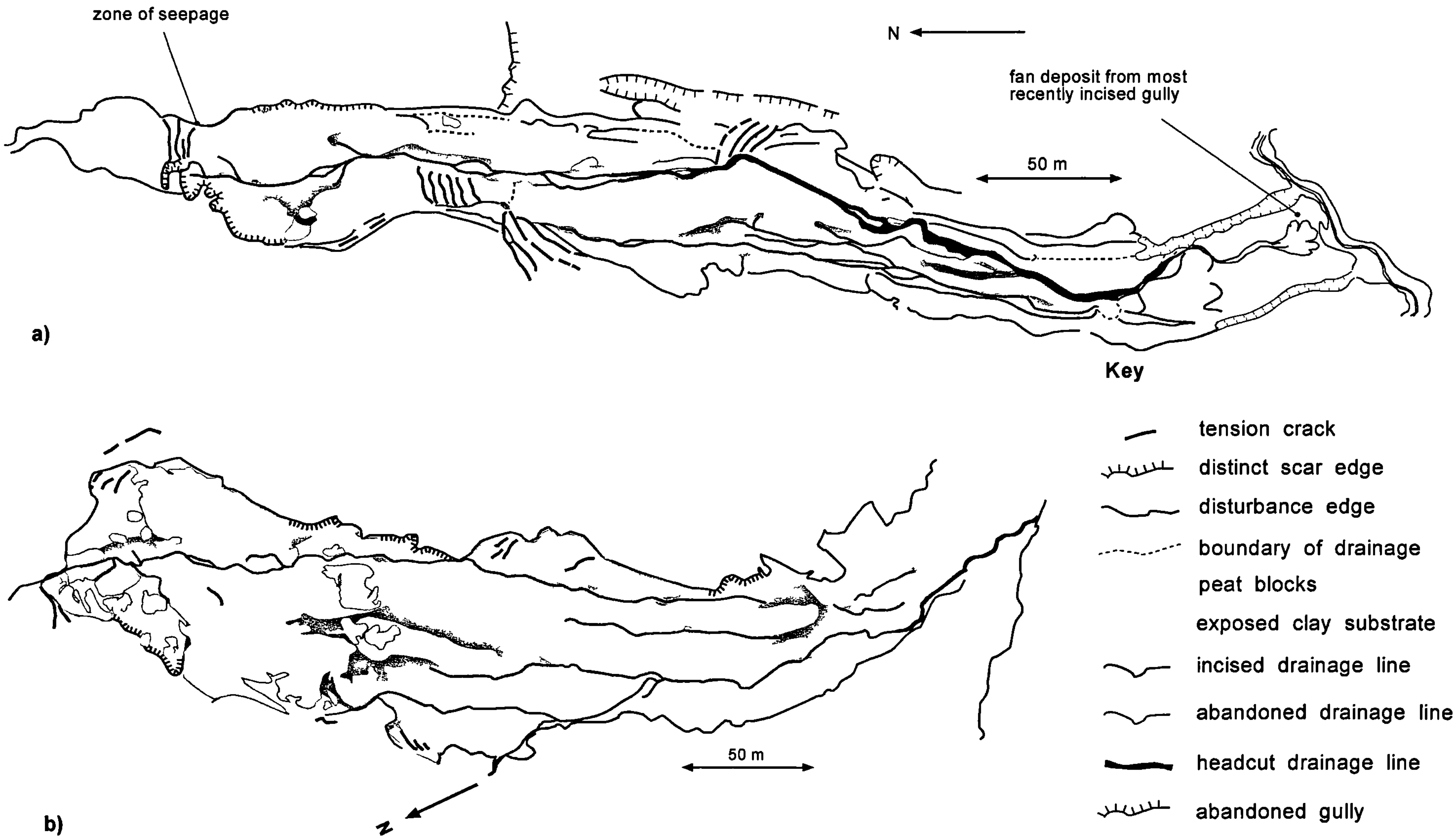


Figure 7.10. Contrasting drainage patterns with increased scar exposure.

Absence of incised drainage lines at a) Meldon Hill, and b) Iron Band in the immediate aftermath of failure - note multi-thread surface drainage as a possible precursor to rill initiation. Well developed drainage at: c) Hart Hope, aggressive head-cutting of the left bank channel; d) abandoned gully at the base of the Hart Hope scar; e) waterfall/cascade at the base of Langdon Head

Figure 7.11. Block wasting at Nein Head 2.

The blocks have been deposited on the right bank in the upper scar area. The photograph taken in March 1984 indicates that the blocks were formerly much larger. Inspection of the blocks reveals dessicated, exposed faces and dislodged debris (ravel) trampled down by sheep. March 1984 photo provided by kind permission of I.Forbes.

In contrast, drainage appears more diffuse in the wider scar at Langdon Head. Frequently drainage lines are disconnected and terminate in diffuse wet zones across the middle and upper scar. Two major zones of seepage feed separate left and right bank side systems, with the former terminating within a blockfield in the lower reaches of the scar, and the latter contributing to minor headward stream recession at the foot of the scar. The lower slopes of Langdon Head are less steep than at Hart Hope, although shortly after the confluence of the scar with the main valley, a waterfall of nearly two metres in height occurs (Figure 7.10e).

Initial comparison of these two scar types suggests that linear scars may be more prone to active channel incision than broader scars, whose surfaces are dissected mainly by shallower rills. Geomorphological maps presented in Chapter 4, and the vegetation maps presented earlier support this idea. Other linear slide scars such as Feldon Burn also exhibit rapidly retreating headcut channels (with step and pool sequences).

Morphological smoothing appears to occur at older slide sites. Comparison of ground photographs at Nein Head 2 (Figure 7.11), Iron Band and Meldon Hill (e.g. Figure 7.10a and b), in combination with field observations suggests that over time, scar margins reduce in height, blocks reduce in size and cracks and tears infill with sediment. The presence of dry ravel at the base of dry and cracked scar margins suggests that the bare peat faces are being weathered. This may be by a combination of frost action, dessication and wind. In addition, the frequent observation of sheep hair rubbed into the coarser top mats of vegetation along scar edges suggests that scars are used both as windbreaks and as 'rubbing' points for grazing animals. It is frequently the case that animal droppings are found mixed in with the debris at the base of scar margins. Similarly, blocks appear to act as windbreaks and rubbing points. Furthermore, they are usually super-elevated relative to the bog surface, and as such completely hydrologically disconnected from the peat blanket (unlike the scar margins). They are consequently far more prone to dessication shrinkage than are the scars (Figures 7.11a and b).

Cracks and tears may infill through similar processes, and margins are trodden in by animals. In addition, many cracks are water filled and act as drainage lines which continue to supply erosive and turbid water to the crack sites. Larger tears are frequently found to be water-filled, and show evidence of pond vegetation succession sequences (see Chapter 3, Figure 3.7f).

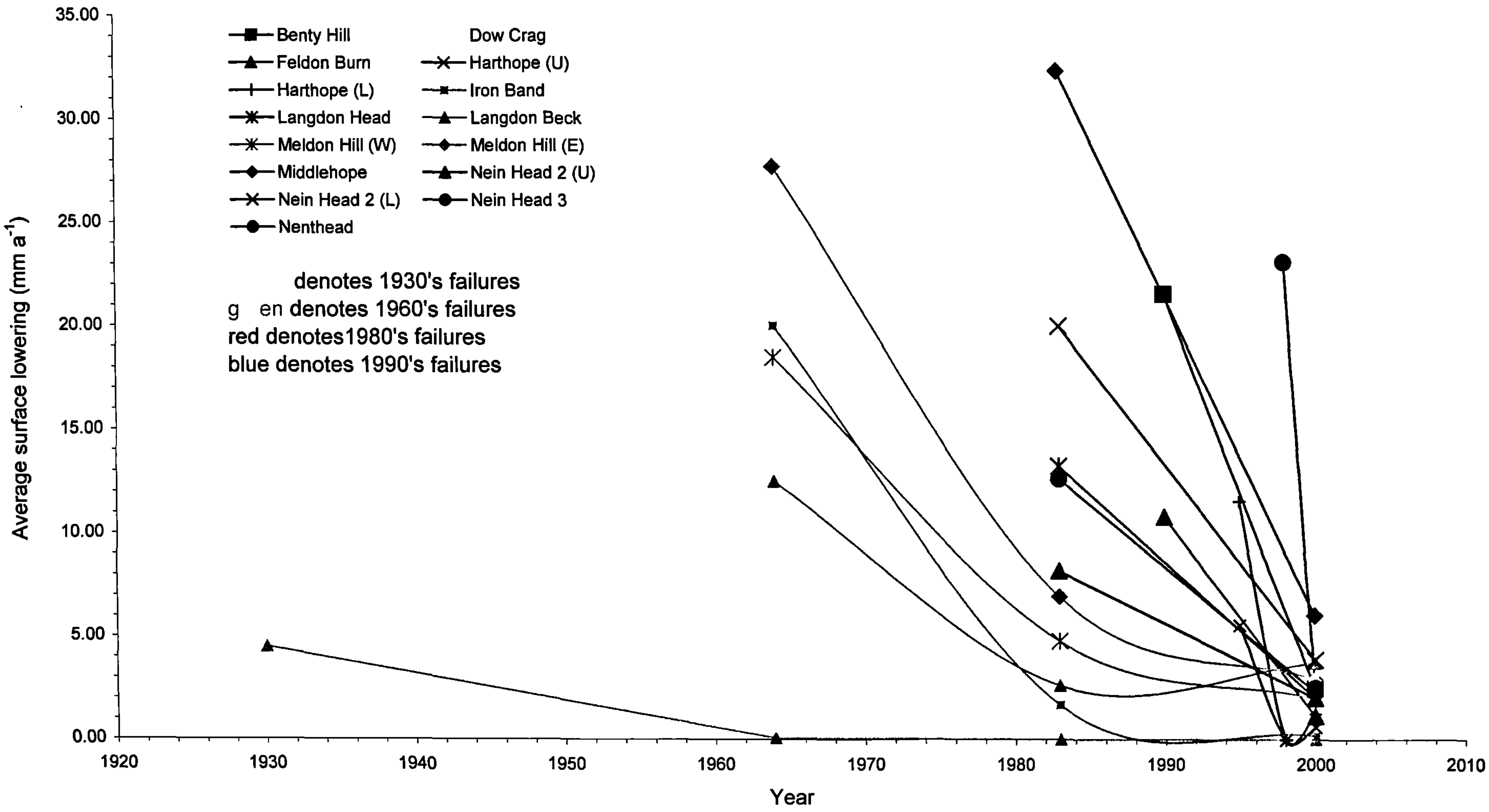
In the light of this evidence, and the vegetation coverage information described previously, the R.U.S.L.E. was applied to each site, assuming a lack of surface drainage in the immediate aftermath of failure. Eight scenarios were used. These and the associated predicted soil losses are described below.

7.2.3.1 The use of the Revised Universal Soil Loss Equation in predicting sediment loss from changing peat slide scar surfaces

Scenario one simulates present day vegetation cover and soil parameters for all slide sites in the North Pennines. The R.U.S.L.E. factor approach was applied to each site to calculate estimated soil loss for the twelve months of the year 2000. Yields in tonnes/acre (the output units for R.U.S.L.E.) were converted to tons/hectare, and using an average site dry bulk density for clay of 1.58 g cm^3 translated into mm of surface lowering per year (mm a^{-1}). The rate of surface lowering was lowest at Dow Crag (0.01 mm a^{-1}) and Iron Band (0.18 mm a^{-1}), and highest at Middlehope (6.00 mm m^2 a^{-1}) and for the lower scar of Nein Head 2 (3.85 mm a^{-1}). Despite the low values at the two Stainmore sites, values at the other three older sites (Meldon Hill East and West, and Langdon Beck) are relatively high. With the R (climate) and P (management) factors held constant, it is the high LS (slope) factors and C (cover) factors that explain the relatively high rates. The upper and lower slopes of Hart Hope and Nein Head 2 were run through R.U.S.L.E. separately as their total slope length exceeds the 1000 ft (305 m) permissable in the model. In the latter case, the scars are effectively separated, and this treatment is appropriate. At Hart Hope, the upper segment remains connected to the lower, but only by a thin bottleneck at the base of the upper slope. In both Hart Hope and Nein Head 2, lower (and steeper) slope degradation is higher than in the upper, shallower slopes.

Scenarios 2 - 5 simulated changing scar surface conditions from failure for each site. R.U.S.L.E. runs were conducted in an annual sequence from the year of scar exposure to the year 2000. Data for vegetation cover and soil textural changes was used to annually modify the R.U.S.L.E. factors. These simulation runs were expected to produce the highest yields, as the factors at scar exposure simulated the minimum possible level of soil surface protection. Sediment loss was far higher immediately after failure than subsequently. This is illustrated on Figure 7.12, which represents changes in average surface lowering through time for all sites. Steep declines in rate are visible at all sites, except Dow Crag, which exhibits a low initial yield rate (4.46 mm a^{-1}). Apart from Coldcleugh Head, which exhibits a rapidly declining yield rate in the two years from failure to the contemporary run, the slopes of the remaining slides are relatively

Figure 7.12. Decline in average surface lowering at all failure sites as simulated by the R.U.S.L.E.



similar, and suggest a broadly equivalent rate of decay in sediment yield.

Peak values across sites are found at Middlehope (32.33 mm a^{-1}), Meldon Hill East (27.71 mm a^{-1}) and Coldcleugh Head (23.09 mm a^{-1}). In the absence of vegetation cover, yield rates should vary only with soil and morphometry. LS factors in each case are among the highest values relative to other slides failing at the same time. Interestingly, in the case of Nein Head 2, revegetation and its effects on the C factor (a decline from 0.446 to between 0.064-0.09) reduce the disparity between rates in the upper and lower scars with age. Yield rates on initial exposure were approximately 2.5 times higher on the lower scar than the upper in 1983, but less than two times higher in 2000. This reflects the key factor related to ageing of sites, the C factor, which experiences the largest changes between time periods for the simulation runs. LS and K remain relatively similar with age, while C factors vary by an order of magnitude.

The final set of three scenarios, 6 - 8 tested the effects of variation in slope, soil and vegetation parameters on the Meldon Hill East site, while holding all other factors constant. This assisted in checking that R.U.S.L.E. results had a sensible physical basis, given variability in vegetation, soil and relief. Multiple regression was *not* attempted, as there were only three predictor variables (discounting P and R), of which two (K and C) utilised several common parameters in their calculation, which may have lead to co-linearity in the regression analysis.

In examining the effects of vegetation cover, total coverage was restricted to four levels, 0%, 33%, 66% and 100%, corresponding with the boundaries between cover classes on the recovery maps in section 7.2.3. Cover was varied in three ways. Sites were simulated with rooted canopy cover only (e.g. reeds and grasses), utilising R.U.S.L.E.'s assessment of vegetation effects on canopy derived interception and rainsplash. A second set of runs examined the effects of rootless residue cover only (e.g. mosses and rocks), utilising R.U.S.L.E.'s assessments of surface roughness and protection from rainsplash. A final group of runs represented more realistic combined covers of canopy and residue, based on growth of both. Vegetation change patterns derived from the quadrats presented previously were used to determine relative cover. Initial development of canopy cover and eventual dominance of residue combined the controls mentioned for the previous two runs.

Yield rates were (obviously) the same as the initial scar-exposed runs of scenarios 2 - 5, for 0% cover, but less obviously so at 33% cover (5.54 mm a^{-1}), suggesting a common controlling effect with low level revegetation. At 66% cover, canopy was more effective at retarding yield rates than residue (1.69 mm a^{-1}, against 2.46 mm a^{-1}), while a combination of the two was as effective as 66% canopy cover (1.69 mm a^{-1}). At 100%, residue was least effective (0.95 mm a^{-1}), canopy most effective (0.22 mm a^{-1}) and a combination of the two was of intermediate effectiveness (0.54 mm a^{-1}).

The controlling effects of soil erodibility were examined by holding vegetation cover constant at 0%, and altering soil parameters to best simulate the effects of sealing and crusting, as observed in the field. At the input stage, R.U.S.L.E. considers two main characteristics of soil, namely its control on water transmission to depth, and its bulk properties in terms of texture. These characteristics determine runoff and crusting potential, and the mass of material output as yield. Within the limits of the soil types under consideration (as determined by the physical properties described in section 7.2.1), soil parameters were varied as far as possible to reflect the minimum, maximum and an intermediate crusting potential. The most significant change in a soil related parameter occurs in the K factor. Results suggested that increased crusting potential increased yield rates, from 11.39 mm a^{-1} to 23.09 mm a^{-1}. The limitations of the class ranges used at the input stage will be discussed in section 7.4.

Finally, minimum and maximum slope gradients (upper and lower between 5% - 8.7% and 21.7% - 31.7% respectively) were varied around the actual gradients at Meldon Hill East and according to approximations of minima and maxima at the other slides. A minimum rate of 5.85 mm a^{-1} was generated for bare scars at low slope sites (e.g. Hart Hope Upper) and a maximum rate of 40.02 mm a^{-1} was generated for steeper sites (e.g. Middlehope).

7.2.3.2 The use of reconstructive techniques to back-calculate sediment losses from changing peat slide scar surfaces

On the basis of the dominant geomorphological processes outlined earlier, annual surface lowering was calculated using equation 4 (section 7.1.1). Figure 7.13, Table 7.7 and Figure 7.4 illustrate the temporal relationships between drainage density, rill depth and scar age, and vegetation cover respectively. Due to the limited datasets available in each case, and in the absence of evidence to the contrary, simple linear rates of decline in rill erosion and increase in vegetation were derived from each graph. Revegetation rate (approximately 1.6% per year) was calculated by regressing the change in percentage cover through 0. Predicted drainage density was related to scar size to calculate drainage network length for each year that each slide scar was active,

Figure 7.13. Decline in drainage density with scar age.

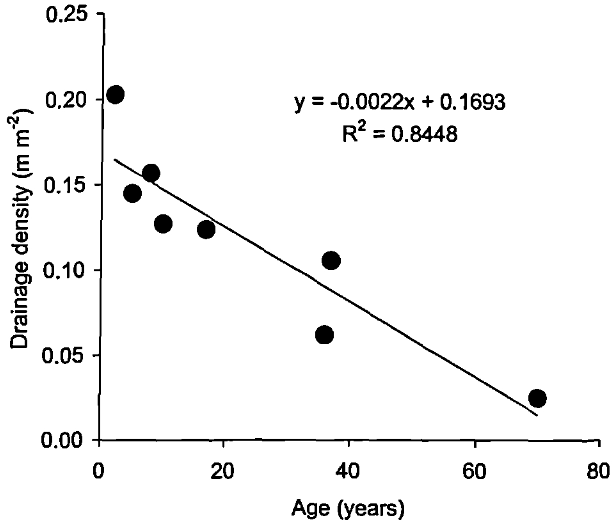


Table 7.7. Mean rill widths and rill depths for all recorded sites

Slide name	Elapsed time (years)*	Mean rill width (m)	Mean rill depth (m)
Hart Hope	5	0.94	0.17
Iron Band	36	0.60	0.30
Langdon Beck	28	1.00	0.25
Langdon Head	16	0.36	0.04
Meldon Hill East	26	0.66	0.23
Meldon Hill Wes	26	0.66	0.23

* time elapsed since photo from which rills mapped

from year of exposure. The field-measured relationship between scar age and drainage density is strong (r^2: 0.85). Consequently, area under rill drainage was calculated by using average field recorded values for rill *width* (Table 7.7) applied across the entire network length. Although this represents a simplification, rill width does not relate significantly to age of failure (Table 7.7), and an scar-age/rill width relationship could not be established as an alternative. The lowering rate from rill erosion was calculated from a linear rate of increase in rill *depth*, as derived from field measured examples (Table 7.7). Annual volume losses by rill erosion are equivalent to the rill area multiplied by rill depth, less the previous year's rill volume. Interrill erosion area was calculated as the bare scar area remaining after vegetation, less the area under rilling. The surface lowering rate for interrill erosion was set as 1 mm a^{-1}, based on an estimate of 20 mm clast exposure in 20 years at the 1980's failures. Total annual site sediment yields equal the combined volumes multiplied by the bulk density of the clay substrate (using a mean value of 1.58 t m^{-3}). Results are considered here in tandem with the R.U.S.L.E. output.

Annual yields derived from both the R.U.S.L.E. method and the indirect field method described above may be compared. Yield rates per hectare from R.U.S.L.E. are applied over the areas of each scar to calculate sediment loss in t ha^{-1} a^{-1}. This is compared with the output of the reconstructive methods, converted from m^3 to t ha^{-1} a^{-1}. Four annual sediment losses are compared across the two methods, with each period following a major event, or cluster of events. Comparisons are made for 1930, 1964, 1983 and 2000. Yields from the indirect field method (reconstructive) are taken from the appropriate year in the site yield tables. Total site sediment yields derived from both methods for the four time periods are shown in Table 7.8, and plots for the latter three periods in Figures 7.14a to c.

Reconstructed values generally exceed those produced by R.U.S.L.E., except for the August 1983 - August 1984 comparison, in which there is a better correspondence between the two methods (r^2: 0.86). Nevertheless, differences between the two predicted yields are usually less than an order of magnitude, which represents a good degree of fit, given the entirely different ways in which site information was managed in each approach.

While these previous approaches have examined the effects of rill and interrill processes, they fail to examine channel development at the scale of gullies (> 0.6 m depth; Selby, 1993). The drainage development maps highlighted earlier (Figure 7.9) indicated that gully formation at the base of both Hart Hope and Langdon Head had

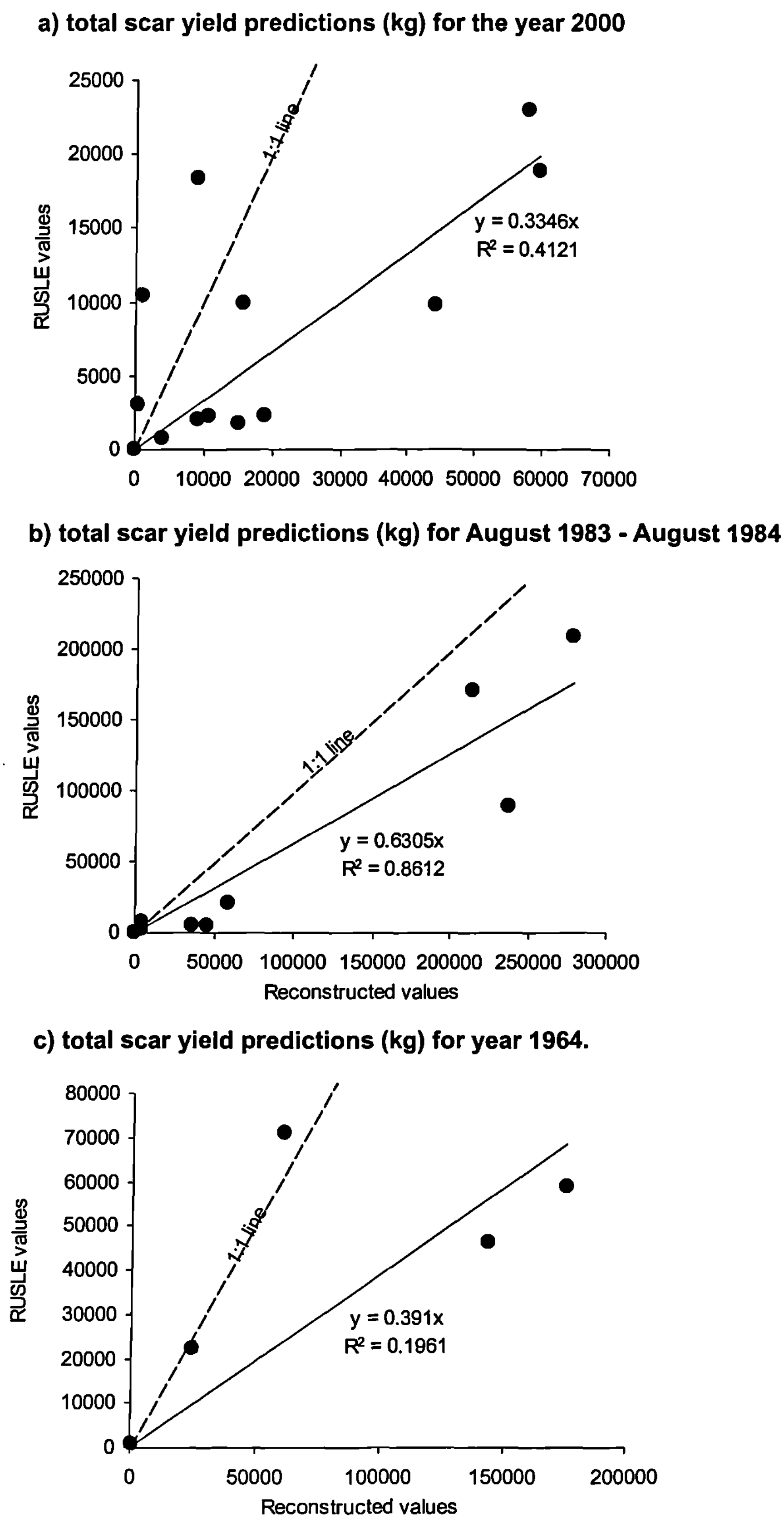


Figure 7.14. Predicted R.U.S.L.E. sediment yields compared to reconstructed sediment yields. 1:1 lines (hashed) and regression lines shown to aid comparison.

Table 7.8. Revised Universal Soil Loss Equation sediment yields compared to reconstructed yields

Site Name	Bare scar area (m^2)	2000 RUSLE predicted loss (kg)	2000 Back calculated loss (kg)	1983 RUSLE predicted loss (kg)	1983 Back calculated loss (kg)	1964 RUSLE predicted loss (kg)	1964 Back calculated loss (kg)	1930 RUSLE predicted loss (kg)	1930 Back calculated loss (kg)
Benty Hill	3750	9236	4700						
Dow Crag	9570	88	0	191	1450	574	4330	42682	70500
Feldon Burn	13858	15786	4850						
Hart Hope	9584	8852	16410						
Iron Band	3045	562	1970	5146	3600	60930	33160		
Langdon Beck	1972	3946	1360	5167	2480	24591	25670		
Langdon Head	16135	59608	18550	213627	148830				
Meldon Hill (W)	5212	19047	4920	45401	9350	175797	86050		
Meldon Hill (E)	9518	15244	2490	36119	4730	144425	43550		
Middlehope	7364	44208	11350	238078	91070				
Nein Head 2	17439	57985	23180	279249	185950				
Nein Head 3	4659	10757	3710	58843	20680				
Coldcleugh Hea(	492	1212	1320						

propagated up scar in the periods elapsed since failure. At Hart Hope, cross-sections were measured at regular intervals up-gully, and used to calculate volumes of excavated substrate for the 5 year period from the failure date (1995). Approximately 804 m^3 of substrate had been excavated, with a total mass of 1,286 t (using a clay bulk density of 1.58 t m^{-3}). This exceeds by some ten times the total losses back-calculated from the rilling component of surface erosion (128.3 t in five years).

7.2.4 The local scale: pre-failure ecological and geomorphic contexts

In chapter 4 (section 4.2.1), consideration was given to pre-failure peat blanket features for sites for which aerial photographic evidence was available. Ground conditions at Nein Head 2, Nein Head 3, Feldon Burn, Hart Hope and West Grain were assessed. The pre-failure photographs provide an indication of the baseline conditions against which recovery can be measured.

The sub-sample of sites revealed a variety of pre-failure ecological contexts, including relatively dry, planar bog surfaces, wetter surface flushlines, and partly vegetated gullies. The vegetation assemblages associated with these would correspond predominantly to grasses such as *Nardus* and *Molinia* in the drier areas, with increasing percentages of mosses such as *Sphagnum* and *Polytrichum* in wetter locations. Ecological recovery would require a return to typical bog species, in order that the biological character of the location remain the same. In the long term, the significance of the peat slide event would be noticeable in a minor change in spatial arrangement of species, and at the patch level only.

In geomorphological terms, some sites acted as throughputs for water prior to failure, and some appeared to be geomorphologically inactive. At Nein Head 3, pre-failure conditions suggest no significant drainage features, and post-failure conditions show little change in downstream channel pattern. The geomorphological effectiveness of scar surface drainage channels is declining as revegetation continues. Nein Head 2 differs from this adjacent site in the development of significant surface drainage features subsequent to failure. Pre-failure conditions suggest that a soakway fed gully occupied the central peat mass. The site has adapted to the loss of the peat body by generating new drainage pathways in the substrate material. Continuing drainage from the scar has widened and deepened the right bank drainage line leading from the scar. This may eventually advance upslope until the scar and gully are directly coupled, and a more efficient pathway for water transport exists than the previous soakway. Similar processes are underway at Feldon Burn and Hart Hope, where channel extension is continuing up-scar, reflecting the position of the scars in former drainage lines (a gully and soakway respectively).

7.2.5 Peat accumulation at old slide sites

Figures 7.15a to c illustrate peat depths recorded by coring at Dow Crag, the oldest of the sites surveyed (70 years). The three cored transects represent two down-slope profiles, one within the scar area, and the second adjacent to the scar area within the undisturbed blanket peat. The third shows a transect taken perpendicular to the downslope axis of the failure.

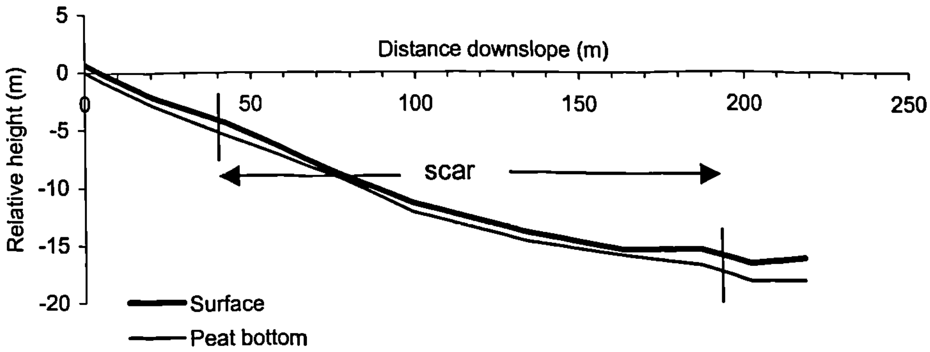
Peat depths off-scar, taken downslope remain reasonably consistent at an average of 1.75 m from above the scar head to the levelling out of slope adjacent to the base of the scar. Comparisons with the on-scar downslope stratigraphy show the limited presence of surface organic matter within the scar area (mean depth 0.58 m), but also surprisingly low depths just upslope of the scar margin (between 0.69 and 0.71 m). At the foot of the slope, peat depths increase markedly within the infilled gully area shown on the vegetation map presented earlier (Figure 7.2).

The across-scar profile indicates peat depths of approximately 2 m to either side of the scar area, with much lower depths within the scar. Peat depths are at a minimum in the scar centre (0.38 m) and deeper at the margins (0.9 to 1.5 m). The level of peat decomposition in these areas is relatively low however, consisting mainly of very slightly decomposed (von Post scale H_2) *Sphagnum* remains and a light grey detrital mud. It appears that infill of the former gully at the base of the slide has led to a 'backing up' of accumulated peat (hence the reversed slope at the base of the downscar transect). It is possible that much of the depth of organic matter described previously is depositional rather than accumulative in origin. Attempts to locate such peat deposits at other failures suggested that bare peat 'floes' did not exist in significant quantities at any site.

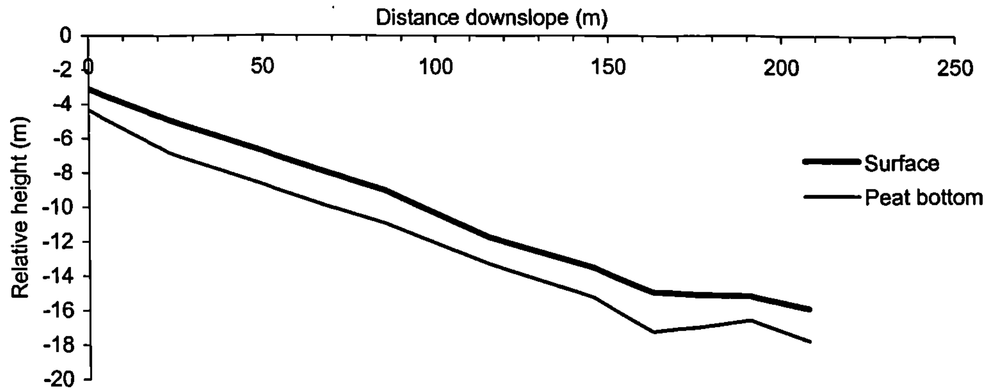
7.2.6 The regional scale: post-failure sediment budgets of North Pennine peat slides, compared with background fluvial activity

This section assesses the regional significance of peat slide activity using a sediment budget approach. The approach reflects the interaction of vegetative, soil and

Figure 7.15a. Down scar changes in peat depth at Dow Crag (2000)



b. Undisturbed blanket scar adjacent peat depths at Dow Crag (2000)



c. Across scar changes in peat depth at Dow Crag (2000)

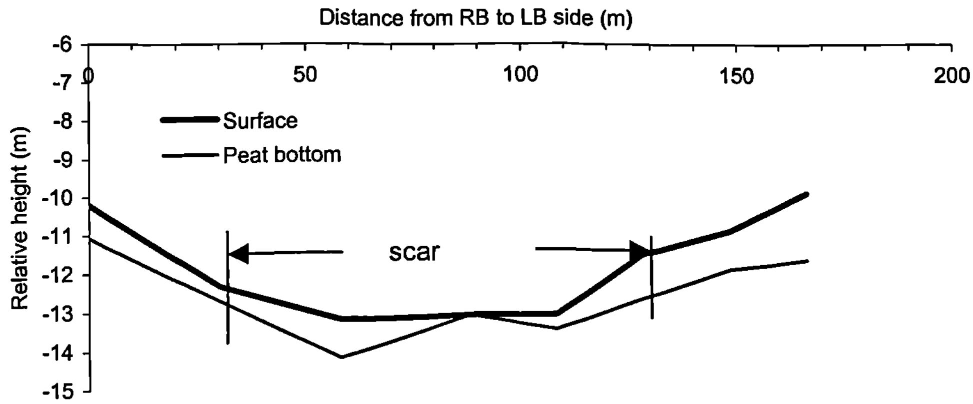
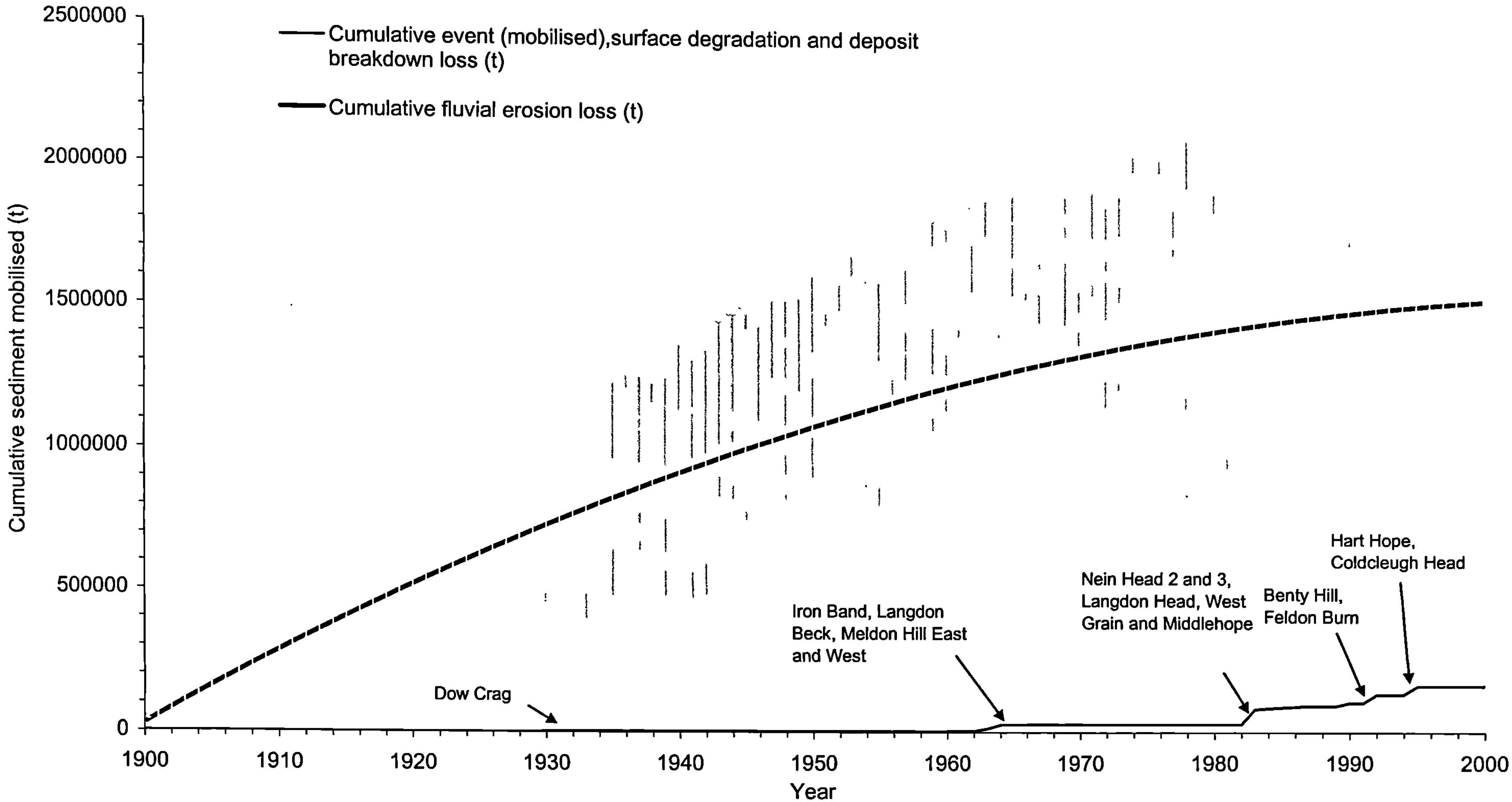


Figure 7.16. Cumulative on-scar, off-scar, event and fluvial mobilised sediment for all North Pennine peat slides.



geomorphic activity at each site, as described in previous sections.

Meso and local scale geomorphic analysis suggested that peat slide scar sites produced significant quantities of sediment in the aftermath of failure. Three periods of sourcing were identified, namely the 'event' phase, the 'deposit breakdown' phase, and the 'surface degradation' phase. 'Event' and 'deposit breakdown' contributions are budgeted as wet weights. The 'surface degradation' phase is budgeted using dry weights. This reflects the differing materials involved in each phase. The peat component ('event' and 'deposit breakdown') derives a majority of its weight from its water content. Dry weight contributions, calculated using bulk data from head scar samples, would be only 16% of the equivalent wet weight contributions. The primary geomorphic effectiveness of peat slides reflects the energy transferred in the wet sediment mass. In contrast, the wastage of dry mineral substrate is 65% of its wet wastage equivalent. Effectively, treating all components of the sediment budget as dry weights would vastly underestimate the actual material mass mobilised during the primary ('event') phase of peat slide geomorphological activity.

Site sediment budgets for the former were conducted in Chapter 4, while the methods for assessment of the latter were outlined in section 7.2.3. The individual and cumulative impacts of these phases are now examined.

Figure 7.16 represents a one hundred year plot of background fluvial activity and slide scar processes for North Pennine blanket peat areas. Sediment mobilised during the event phase, surface degradation and deposit breakdown phases are summed annually for the slide population, from the year of onset of the first failure. Therefore, initially, only Dow Crag contributes to the curve. Iron Band, Langdon Beck and the two Meldon Hill failures add pulses of sediment in the sixties, and the remaining slides are factored in as they occur. Fluvial rates for the blanket peat areas are based on a simple sediment yield decay rate derived from data of Crisp (1966) and Evans and Warburton (2001) (section 7.1.1). Cumulative sediment yields are calculated for the North Pennine region using the area coverage of eroding peat mapped by Bower (1960). 50% error bars are applied to this estimate due to the level of simplification assumed in generating the rate.

The contribution of individual slide events to the curve is of less interest than the relative contributions of the different phases of slide activity to sediment yields. Over the full time period in which peat slides have occurred, surface reworking has accounted for an extremely small percentage (0.17%) of sediment transport next to wider background fluvial processes. Most of this contribution has been made in the last 20 years, from the collective large scar areas of the Noon Hill 1983 cluster. With the addition of slurry breakdown and export, the sum contribution of peat slide related processes increases to 1%. Again, much of this contribution derives from peat slides occurring in the last twenty years. Adding the peat slide events themselves increases the peat slide sediment yields to an equivalent of 3% of the fluvial contribution. Mobilised sediment (i.e. sediment actively transported at some point in time, but not necessarily delivered), shown in Figure 7.16 and plotted at the same scale as fluvial loss, represents an equivalent of 7.8% of the fluvial contribution. This is significant, as although peat slides may mobilise considerable volumes of material, only that which is coupled impacts outside the locality of the peat slide scars. According to this simulation, the relative significance of peat slide events and background fluvial activity appears to be changing with time. Fluvial yield rates are declining (supported elsewhere, e.g. Evans and Warburton, 2001), and the contribution of peat slides is increasing.

Site Name	Event mobilised (m^3)	Post failure scar mobilised (m^3)	Post-failure deposit mobilised (m^3)	Total material mobilised (m^3)	% of total mobilised represented by event
Benty Hill	4880	43	725	5648	86.4
Coldcleugh Head	420	6	235	661	63.5
Dow Crag	14425	269	1360	16054	89.9
Feldon Burn	8875	53	1185	10113	87.8
Hart Hope	18655	915	1427	20997	88.8
Iron Band	7960	110	460	8530	93.3
Langdon Head	18750	360	340	19450	96.4
Meldon Hill (W)	3940	289	289	4518	87.2
Meldon Hill (E)	1825	145	435	2405	75.9
Middlehope	3645	208	620	4473	81.5
Nein Head 2	22925	426	3375	26726	85.8
Nein Head 3	6200	67	3200	9467	65.5
West Grain	870	54	870	1794	48.5

Table 7.9. Relative event and post-failure mobilised sediment volumes

Table 7.9 illustrates the relative volumes of sediment mobilised in the events themselves, and subsequently. Most of the sedimentary significance of peat slides relates to the initial events, rather than subsequent reworking of the scar surface material. Between 48 and 96% of sedimentary activity occurs during the failure events themselves, with post-failure activity amounting to only a small percentage of sediment mobilised. It is not yet known whether continuing channel development at Hart Hope and Feldon Burn will give rise to longer term contributions to local sediment budgets.

7.3 Discussion

The two main aims of this chapter have been to examine the mode of slide scar recovery in the medium (10^1 a) and long term (10^2 a), and the significance of peat slide scars in the landscape. Four hypotheses were proposed in section 7.0, reflecting these aims, and considering the collective influences of vegetation, geomorphological processes and soil development on recovery. Recovery was defined as a return to landscape conditions equivalent in function to those pre-failure at each site. This section collates data from the micro- to the regional scale in considering the effectiveness of recovery processes at slide sites. This information is formalised in a model of peat slide scar recovery.

The first hypothesis suggested that recovering slide scars would exhibit distinct spatial patterns and temporal sequences of plant communities with increasing age. This was examined through the use of quadrats, transects and vegetation maps. Vegetation coverage at the quadrat scale suggested a near linear increase in vegetation cover with increasing age (section 7.2.1), following a short period of priming of the scar. Initial loosening of surface structure by erosion and weathering would allow the growth of the hardier species, such as rushes and grasses. Grasses such as *Nardus* and *Molinia* would initially occupy the flatter drier scar areas, and rushes, such as *Juncus* develop in surface drainage lines. *Polytrichum* moss would become associated with *Juncus*, and flowering species such as *Galium* with the grasses. Over the first twenty to thirty years, species diversity would increase, but complexity of distribution decrease. Transects indicate that rushes and mosses would occupy linear drainage features, and grasses and flowering species the drier scar areas and block and raft tops that are disconnected from the surrounding peat blanket. This increased homogeneity of vegetation cover is shown in Figure 7.17. Increasing stability from plant roots and associated increased surface moisture retention would allow species characteristic of wetter environments to colonise after a period of thirty years or more (as evidenced by *Sphagnum* cover at Meldon Hill East and the older slides). Species diversity would peak prior to the onset of these moist, acidic conditions, and then decline thereafter as mosses and increased rush cover form a continuous blanket over the scar areas (such as at Dow Crag).

These trends in vegetation development can be related to soil chemical and physical changes, incorporating the aims of the second hypothesis. Exposure of the scar substrate revealed a heavy textured material, of a clay-like consistency, but with a significant sandy fraction derived from weathering of small clasts at the surface and

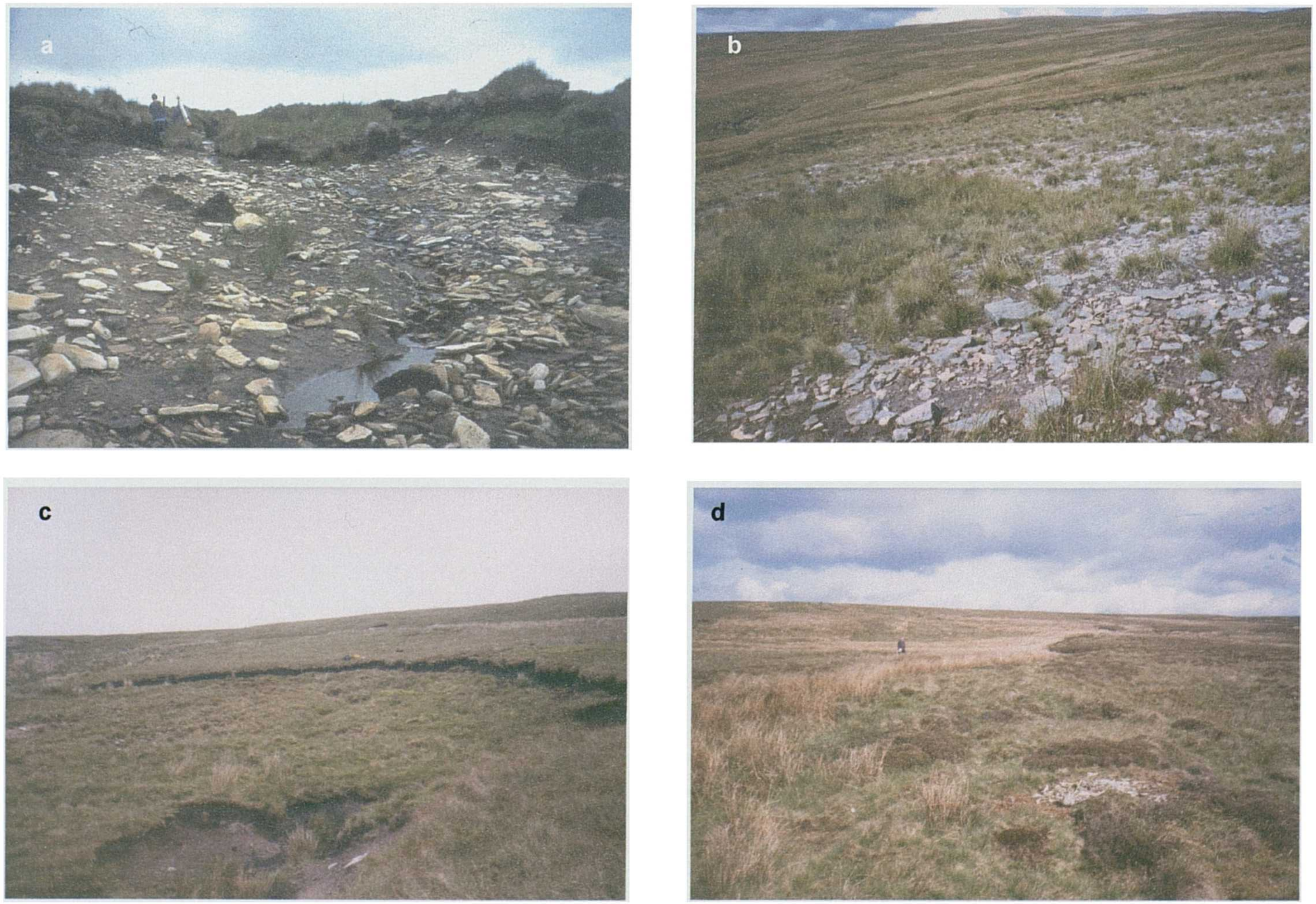


Figure 7.17. Four slides of differing age, showing increase in vegetation cover, and decline in geomorphic activity: a) Hart Hope (1995), incision into bare scar visible in foreground; b) Middlehope (1983), effects of wash and incision clearly indicated by extensive stone cover at scar surface; c) Iron Band (1964), scar surface almost completely vegetated, drainage activity minimal except for small channel fed by pipe on near-side; d) Dow Crag (1930), figure stands within scar area, no clear morphology evident. All photos were taken in summer 2000.

beneath (section 7.2.1). Grain-size distributions suggested that clay content increased with depth, and this was attributed to surface modification of substrate sediment, with the formation of micro-aggregates from the smallest clay fractions increasing with age, and most active at the scar surface. Table 7.6 suggested that wash, sealing, crusting and cracking all operated more effectively in the lower slopes than nearer the head scar (section 7.3.2). Increasing slope angles in the lower slopes of the recovery sites would also support this variability. The variety and regularity of recorded processes declined with increasing scar age, with evidence of wash particularly in decline in the 1960's sites. Attempts to identify substrate chemical changes achieved limited success. Although the quantity of available nutrients was shown to become more variable across a greater range of values, consistent increases in availability could not be defined across the chronosequence of scars. Nevertheless, increased mineral nutrient availability would favour continuing revegetation and reflect increased nutrient cycling. pH was seen to rise with increasing vegetation cover, until sufficient vegetation growth signalled a return to wetter and more acid conditions. Organic matter content showed no significant relationship to scar age. The generally acid conditions and heavy substrate at all sites would preclude the operation of macro-organisms in mixing organic matter. It is possible that a more generous sampling framework incorporating more samples would elucidate temporal trends.

The third hypothesis reflected the role of scar surface geomorphological processes in regulating recovery rate. This was primarily examined at the site scale through a combination of modelling and reconstructive approaches (sections 7.2.3.1 and 7.2.3.2). Recovery maps provided the basis for many of the calculations (section 7.2.3). Sediment yields from the slide sites were highest in magnitude in the immediate aftermath of scar exposure under zero cover conditions and in soils unmodified by subaerial weathering and erosion. Yields declined rapidly with increasing vegetation cover and changing soil character (permeability, particle size and surface roughness). The steepest scars (Middlehope and Nein Head 2) were found to be the most prone to erosion. Increased slope gradient increased erosion yields, while increased vegetation cover had the reverse effect. Rushes and grasses provided more effective cover than mosses and rocks. Increased crusting potential, embodied mainly in an increase in the coarse fraction of surface soils, produced higher sediment losses. Site specific case studies (at Hart Hope and Langdon Burn; section 7.2.3) suggested that channel related yields in the first five years after failure could exceed those of rill and interrill erosion by up to five times. The gully system at Hart Hope continues to advance with channel migration active in the lower scar area. It is possible that extension will continue upslope beyond the head scar limits.

The long term significance of peat landslides was investigated through a regionally based assessment of slide sediment yield, compared with background fluvial activity in peat catchments. Temporal subdivision of slide activity into event, slurry breakdown, and surface modification phases illustrated that the event phase was by far the most significant in terms of sediment yield. Post-failure sedimentary activity on slide scars would continue until the scars were completely revegetated, but at a decreasing rate. A backdrop of decaying rate of fluvial erosion in the North Pennines, and increasing frequency of peat failures posits an increased significance for peat slides as geomorphic agents in the region.

Some indication of control upon geomorphic activity was provided through comparison with pre-failure peat blanket conditions. Peat slide scars in former drainage lines indicated self-regulating attempts by the disrupted flowpaths to establish new drainage pathways through the failed hillslope segment. The effectiveness of this self-regulation, relative to vegetation and soil development, is largely embodied in the development of a stable cover. Evidence from the oldest site, Dow Crag, suggested that some peat accumulation has occurred over the scar area, although not necessarily by development in-situ. However, the conditions at Dow Crag support a return of peat slide sites to geomorphic stability, but not to an approximation of either the original pedological or ecological conditions. The major criticism of the chronosequence in general is that it does not span a time period appropriate to long term peat accumulation. This is a function of data availability, rather than methodological approach.

The final hypothesis considered the nature of the recovery state, and is embodied in the recovery model. Figure 7.18 shows a model of peat slide scar recovery for the North Pennines. Five characteristic 'snapshots' are shown, each reflecting a significant phase in terms of geomorphological, ecological or pedological development. The first three stages are based on observations and data presented in this chapter, whilst stages 4 and 5 are based upon assumed trends.

Stage 1 (0 - 1a)

Peak of post-failure geomorphic activity, formation of micro relief in wet months through development of sheetwash, shoestringing and rilling, possible gully formation in lower, steeper gradient slopes, cracking of exposed substrate surface in summer months; preliminary structural changes at surface under subaerial weathering, drying of upper layers of substrate, and localised oxidation. Colonisation by vegetation largely absent.

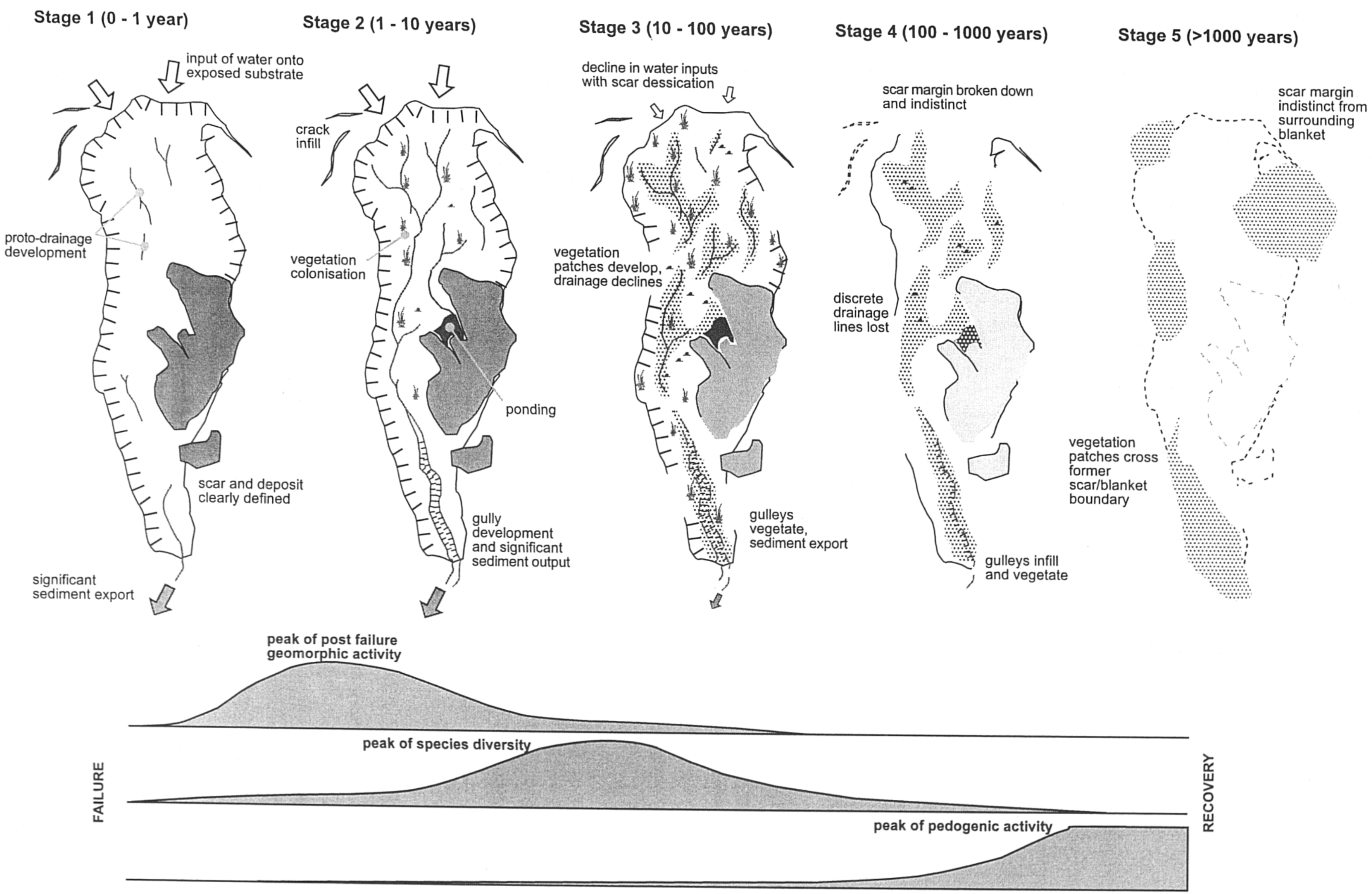


Figure 7.18.Temporal framework for peat slide scar recovery in the North Pennines

Stage 2 (1 - 10a)

Vegetation colonisation begins, initiating with pocking of grasses on micro-elevated substrate, and rushes in more established rills, and around scar margin, semi-permanently waterlogged by free-drainage from exposed scar walls; root action and continued geomorphic activity continue structural breakdown of substrate surface, drainage network becomes established, with increasing channel depth and capacity downslope; sediment export from scar into local channel systems may reach a peak since failure; local washing and sedimentation occurs, infilled micro-relief acting as focus for further rush growth; scar margins liable to dessication and collapse in summer; dry export of micro-aggregates of peat by wind.

Stage 3 (10 - 100a)

Established species spread and stabilise, mosses (including *Sphagnum*) develop in decreasingly active rills and local concentrations of drainage; plant communities develop forming distinct patches of common species - in long enough failure scars, these may show an altitudinal gradient; gully extension will cease if upslope supply is sufficiently reduced by vegetation, and regional sedimentary significance of slide scar declines; scar margins continue to shrink and collapse; physical changes in substrate accompany chemical alteration - nutrient cycling initiates, pH begins to decline as waterlogging increases.

Stage 4 (100 - 1000a)

Complete vegetation cover established and geomorphic activity ceases; scar margins incorporated into continuous vegetation mat, spreading from scar over undisturbed blanket; scar retains water for longer periods, peat forming species expand at the expense of grasses and flowering species, species diversity declines; pH stabilises; nutrient cycling declines; peat accumulation initiates very slowly.

Stage 5 (> 1000a)

Altitudinal difference between scar and surroundings reduces until scar is no longer a focus for drainage; surface conditions now equivalent to surrounding peat mass, and vegetation communities cross scar-undisturbed boundary; peat may have formed to limited depth in scar basin.

This model has two significant implications. The first is that peat slide scars are ephemeral features in the blanket peat landscape. Their formation is instantaneous in a timeframe of peat accumulation, and their reincorporation into the landscape varies according to landscape context. The second is that the current peat slide set does not represent the total population of peat slides that have occurred in the North Pennines. The first implication is best considered in the context of a return to pre-failure conditions in vegetation, soils and geomorphic activity.

Ecological recovery is the most rapid. Full vegetation colonisation may take place in under 100 years. Similar periods have been cited for other recovering landslide scars in non-peat environments (e.g. Lambert *et al*, 1984; Trustrum and DeRose, 1988). The species assemblages that result are typical of the peat blanket environment, in that they are comprised of the same species set, although they may be distinctive at a patch-level relative to other local assemblages. Local diversity in vegetation patchiness is a feature of blanket moorland, with variations in species composition associated with topography and surface drainage features. In this respect, peat slide scars become irrelevant as ecological disturbances over relatively short timescales.

Geomorphological recovery is closely tied to vegetation development, since a full scar vegetation cover will generally preclude further geomorphic activity. A cessation of geomorphic activity reflects a return to pre-failure landscape stability, and hence recovery. However, evidence suggests that slide scars may still form the focus of drainage lines, where the previous peat mass was a flush, soakway or was at the head of a gully. For the period in which the scar is partially vegetated, sedimentary activity may be significant on a local scale. Where gullying takes hold, the period of geomorphic activity may be prolonged (such as may occur in coming years at Hart Hope) and of greater significance. In either respect, geomorphological activity, in most cases, may be seen to return to the pre-failure state within a similar timescale of between 50 and 100 years. Patterns of geomorphic activity witnessed at peat slide sites are similar to those recorded for other recovering landslide sites (e.g. Lundgren, 1978; Pandey and Singh, 1985; Westerberg and Christiansson, 1999).

Pedological recovery is less clear. Strictly speaking, the formation of new peat deposit within the landslide scar, and its accumulation to depths equivalent to those pre-failure would represent pedological recovery. Short term (in the context of soil/peat development) changes in nutrient availability, pH and structure suggest minor changes in 'soil' state over the periods of ecological and geomorphological recovery cited previously. However, other than an increased acidity, the changes do not signify a strong tendency towards peat accumulation in themselves, nor towards the higher nutrient statuses of recovering scars in other environments (e.g. Flaccus, 1959; Douglas *et al.*, 1986; Guariguata, 1990; Blaschke *et al.*, 2000). Given that the cooler and wetter conditions responsible for peat accumulation in the past no longer dominate, peat accumulation would not be expected. Furthermore, the changes in exposed substrate qualities that do occur are not significant enough that they can be said to control the rapid encroachment of vegetation within the slide scars. It is possible that bog species are more limited by pH than low nutrient availability (to which they are adapted), and it is the period of higher pH's between 15 and 30 years in age that prevent the development of peat forming species such as *Sphagnum*.

The implication of these statements is that 'historic' slide scars, pre-dating the known North Pennine sample, should still be present as subtle depressions in the landscape. While all traces of deposit may be expected to have degraded since failure, mainly through shrinkage, the scars should exhibit anomalous peat depths (in the order of a few tens of centimetres) relative to the surrounding thick peat blanket. However, the visibility of these scars is likely to be obscured by similar vegetation communities to those in the immediate surroundings. Because rooting depths for characteristic bog species are low, only a small degree of peat accumulation (or even development of organic soil) would be required for increased uniformity in species type across the slide area. Given the focus for drainage represented by the scar depression, preference for waterlogging, acidification and pedogenic development of peat (Taylor and Smith, 1980) would be concentrated in the slide scar areas.

For these reasons, it is unlikely that it will be possible (other than by extreme fortune) to locate further peat failures in the study region. Therefore, the impression that peat slides are an increasingly important geomorphic phenomena is potentially unfounded, despite the justification for an increase posited by climate change, increased storminess, and the concept of there being natural intrinsic limits to peat bog accumulation.

The next chapter considers the empirical data presented for peat slides in this and the previous chapters, with a case study of a bog burst feature in Northern Ireland. This provides a context for the discussion peat slide significance, and peat mass movements in general as geomorphological agents in peat environments, undertaken in Chapter 9.

8. FORM, PROCESS AND LANDSCAPE SIGNIFICANCE OF BOG BURST EVENTS

8.0 Introduction

Evidence of peat slide morphology, material characteristics and post-failure processes have been presented. Justification for focus on peat slides as a specific landform type in peatlands, was made on the basis of a dual classification of peat mass movement (Figure 2.13). This chapter provides a comparative case study of a characteristic bog burst feature, on the basis of the definition in Chapter 2 (section 2.2.2). The morphology, materials and recovery of the Glendun bog burst are considered in the light of previously presented data concerning peat slides. The evidence for differences between bog bursts and peat slides are evaluated. The primary aim is to establish whether there is a justification for a process and/or form-based distinction between peat slides and bog bursts. The secondary objective is to assess the value of the methodological frameworks used for peat slides in the elucidation of bog bursts.

8.1 The Glendun bog burst, Co. Antrim

The Glendun bog burst is one of a suite of landslides that occurred in Co. Antrim, Northern Ireland, during heavy rain in November 1963 (Colhoun *et al.*, 1965). While many of the failures were coastal mudslides, two bog bursts were reported, of which the Glendun failure is the largest. County Antrim has the biggest cluster of events recorded in either Ireland or Northern Ireland (Figure 2.3), with both peat slides and bog bursts recorded for at least 200 years (Sollas *et al.*, 1897; Tomlinson and Gardiner, 1982; Wilson and Hegarty, 1993). Both the upland blanket bogs and lowland raised bogs of Antrim are under pressure from natural and human-induced erosion (Tomlinson and Cruickshank, 1990). In an aerial photographic survey of Northern Ireland peatlands, Tomlinson and Cruickshank (1990) identify four additional failures in the vicinity of the main Glendun failure. Two of these were field verified as bursts as part of this case study.

The burst disturbance area is several hundred metres in length and over two hundred metres wide (Figure 8.1). It consists of two main zones of subsidence, partially separated by a substantial stable central peat body (Figure 8.1: 11). The scar heads are scalloped (Figure 8.1: 5-8) and poorly excavated (Figure 8.1: 2), with hundreds of closely spaced peat rafts. Below the stable peat mass, the scar becomes more excavated (Figure 8.1: 13) and a grass covered plain represents a former peat cover that was probably removed during failure.

The passage of the burst and its debris are described by Colhoun *et al.* (1965) on the basis of field survey the day after the event. They describe the break up of the fibrous surface peat and its transport over a flow of lower, well humified peat. Although many of the blocks were left stranded in the scar area and on its plateau track, a considerable volume of material was funnelled into a hillside gully, leaving a coating of debris up to 15 m above the stream bed. Pre-failure conditions indicated by aerial photographs from 1954 suggested the presence of gullying in the track area, but not in the soon-to-be scar (Colhoun *et al.*, 1965). Climate records for the uplands in November suggested approximately 200-300 mm of rain, with between 40 and 60 mm in the 24 hours prior to the Glendun burst. Colhoun *et al.* (1965) cite this as the cause of failure.

8.2 Bog burst morphology and morphometry

Bog bursts, as with peat slides, may be considered in terms of their characteristic morphological units and the dimensions of their scars and deposits. Previously published morphological maps presented in Chapter 2 suggest that bog bursts are characterised by extensive, amphitheatre shaped disturbance zones of subsided peat mass. Subsidence is attributed to the loss of underlying, fluid peat, which escapes through cracks in the overlying peat, or at breached vertical faces (e.g. channel walls, the blanket margin) at the down-slope extent of the disturbance area. The loss of this basal support permits free drainage of the fluid peat and sets up tension in the surface mass, which breaks up into concentrically arranged raft-tear morphology (e.g. Figure 2.8). The height difference between the top surface of the disturbance area and the surrounding undisturbed mass may reflect the depth of underlying material removed, assuming a broadly planar pre-failure bog surface. Tearing may extend outwards from the main subsided zone, but with only minimal transport of the overlying peat. In these cases, the distinction between 'scar' and 'undisturbed' peat is unclear. It is proposed that 'disturbance area' is used as an all-embracing term to describe the maximum extent of tearing and/or excavation within the peat blanket.

The rafted forms at bog bursts differ in dimension to the rafts found in the upper slopes of peat slides. Concentric tearing produces long, arcuate peat masses, pictured for

Figure 8.1. An aerial photograph of the Glendun bog burst, illustrating key morphological features (Photo taken in 1999, failure occurred in 1963).

1. Scar head near hillslope summit, well defined, with clear boundary between disturbed and undisturbed peat.

2. Central blockfield in upper disturbance zone.

3. Parallel rafts and tears on left hand side of scar - tears are lighter (filled with *Eriophorum vaginatum*) and rafts darker (*Calluna vulgaris*).

4. Linear revegetated drainage features that have exploited gaps between rafts and blocks.

5 - 8. Multiple scalloped source areas, each with elongate rafts breaking down into block forms with increasing transport distance.

9. Secondary blockfield.

10. Another blockfield.

11. Stable central peat mass, with tearing at margins.

12. Another linear drainage feature.

13. Largely block and raft free lower scar area, surface conditions likely to be similar to peat slides of similar age.

14. Grass-covered run-out zone before major slope break, no depositional evidence.

15. Peat blanket margin.

Note also the extensive patterning of drainage cut around the scar margin, presumably in an attempt to prevent further instability.

100 m approx

N

Glendun in Figure 8.1. Time restraints prevented a detailed survey at the Glendun site, and block measurements were not undertaken due to time constraints. Metric dimensions of the rafts are therefore not available. However, major (a-) and minor (b-) axes may be plotted as ratios of the largest rafts in the population (n > 200). These are shown with peat slide raft, sub-component and block data grouped and treated as ratios in the same way (Figure 8.2). While the sample population is similar to that for peat slides, many of the larger rafts are elongate, and there is generally greater variability (slides s.d.: 0.10 ; bursts s.d.: 0.13). This suggests that there is some morphological difference between the two forms. Although aerial photographs could not be obtained for other bog bursts, ground photography at Straduff and Slieve-Rushen (Figure 2.8a, Figure 2.10a) indicate similar, relatively elongate forms.

The mode of break up of the peat body at peat slides may differ to that at bog bursts. At peat slides, fragmentation of the larger peat rafts into sub-components and smaller masses appeared to be a function of transport distance, and also mode of arrest (e.g. mounting, jamming). Rafts buckled over the scar margins, and separated due to localized extension in transport. Sub-components demonstrated a clear intermediate in size between rafts and blocks, maintaining similar platey forms and length/width ratios. At the Glendun bog burst (Figure 8.3a), peat appears to detach in parallel strips, peeling away from scar margins or local stable peat (such as that marked 'A' and 'B' in Figure 8.3b). A comparison of many of the larger raft lengths with sub-components of the bending rafts, and with smaller blocks suggests that many of the small peat masses are probably derived from the larger rafts (Figure 8.2b). The dominant elongate crescentic rafts flex around their centres, bend, and ultimately snap into smaller peat masses (Figure 8.3c).

The extensive raft remains at bog burst sites generally, explain the lower degree of excavation cited in Chapter 3. In the lower slopes, raft forms are rare (Figure 8.3a: 'C'), and the dark tones that denote solid deposit top surfaces appear smaller (Figure 8.1). Definition is less clear in this part of the slope, and the greater scope for error in photograph interpretation means that form ratios have not been compiled. However, the change to small block forms mirrors that in the lower slopes of peat slides. This suggests a tendency towards equifinality in deposit form across the two features, and this may explain some of the variability in classification within the literature.

A possible reason for the differing upper scar morphologies of bog bursts and peat slides may be slope angle. Steeper slopes favour instability generally (Selby, 1993), and peat slides occur over steeper gradients than do bog bursts (Chapter 3, section

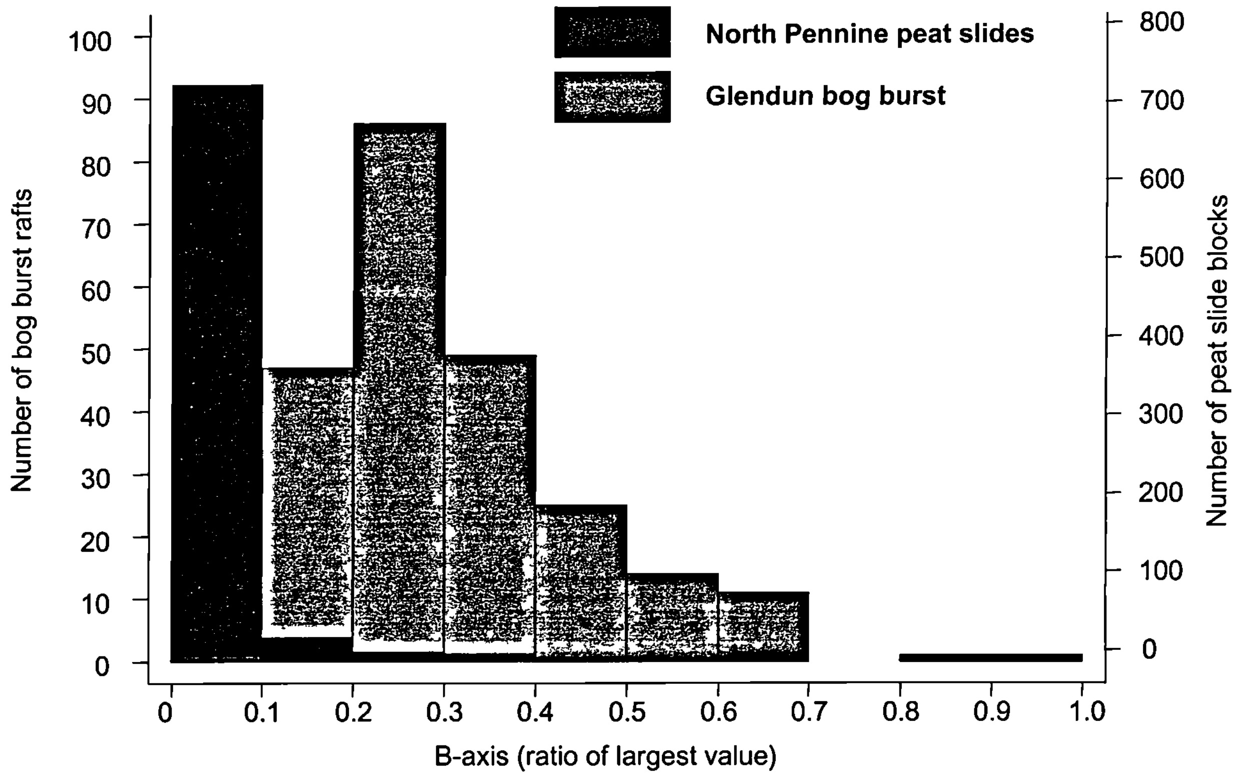
3.1.2.4). Consequently, there is greater likelihood of more complete excavation. Slope angles are very low at bog bursts and there is less impetus for movement of debris downslope. At Glendun, slopes are between 3° and 5° for most of the upper disturbance zone, which extends some 500 m from near the crest of the hill. The distal part of the 'scar' and deposit descends over a steeper valley side, more in common with the slopes over which slide deposits are found (up to 25°). The occurrence of bog bursts on negligible slopes (0 - 2°) in lowland areas (e.g. Solway Moss; Pennant, 1772) and of morphologically similar quick-clay failures on alluvial plains support failure mechanisms largely independent of the effects of relief. Slide morphology is always associated with hillslopes.

A transport mechanism not driven by slope would require a basal shear zone of minimal friction. Such a shear zone might be comprised of a pre-failure fluid peat at depth. There are several reports of 'floating' or 'quaking' bogs, in which unspecified volumes of water, or perhaps slurried peat are trapped beneath the more solid surface peat (Roulet, 1991; Graniero and Price, 1999). Although these are not generally associated with bog bursts in the peat mass movement literature, they represent a possible form of sub-surface water reservoir appropriate to the mechanisms described previously. The material basis for such layers at the Glendun site is considered in the next section.

8.3 Bog burst materials and mechanisms

Figure 8.4 shows a head scar stratigraphy for the Glendun failure, with all bulk properties included except loss on ignition. The profile is notable for its extreme humification and low fibre content. The core sample, pictured in Figure 8.5a and b is both deep (> 2.2 m) and relatively uniform in physical properties. The core is dominated by highly humified peat with fine fibre traces throughout much of the upper 1.5 m. Thin fibrous layers are found between 1.23 and 1.28 m and between 1.72 and 1.83 m. The peat substrate contact is sharp, and is not shown on the stratigraphy because many clasts were found in the upper few centimetres of the substrate and sampling was not possible. In the lower metre of the core, the peat acquires a more elastic feel. The highly humified peat is recorded as a von Post humification of $H_{9\text{-}10}$ from 0.7 m depth. Bulk properties are generally consistent with depth. However, there is a noticeable gentle decline in gravimetric moisture content (%) from 1.45 m, mirrored in a very slight change in volumetric moisture content.

Figure 8.2. Deposit b-axes comparison for North Pennine slides and the Glendun bog burst.



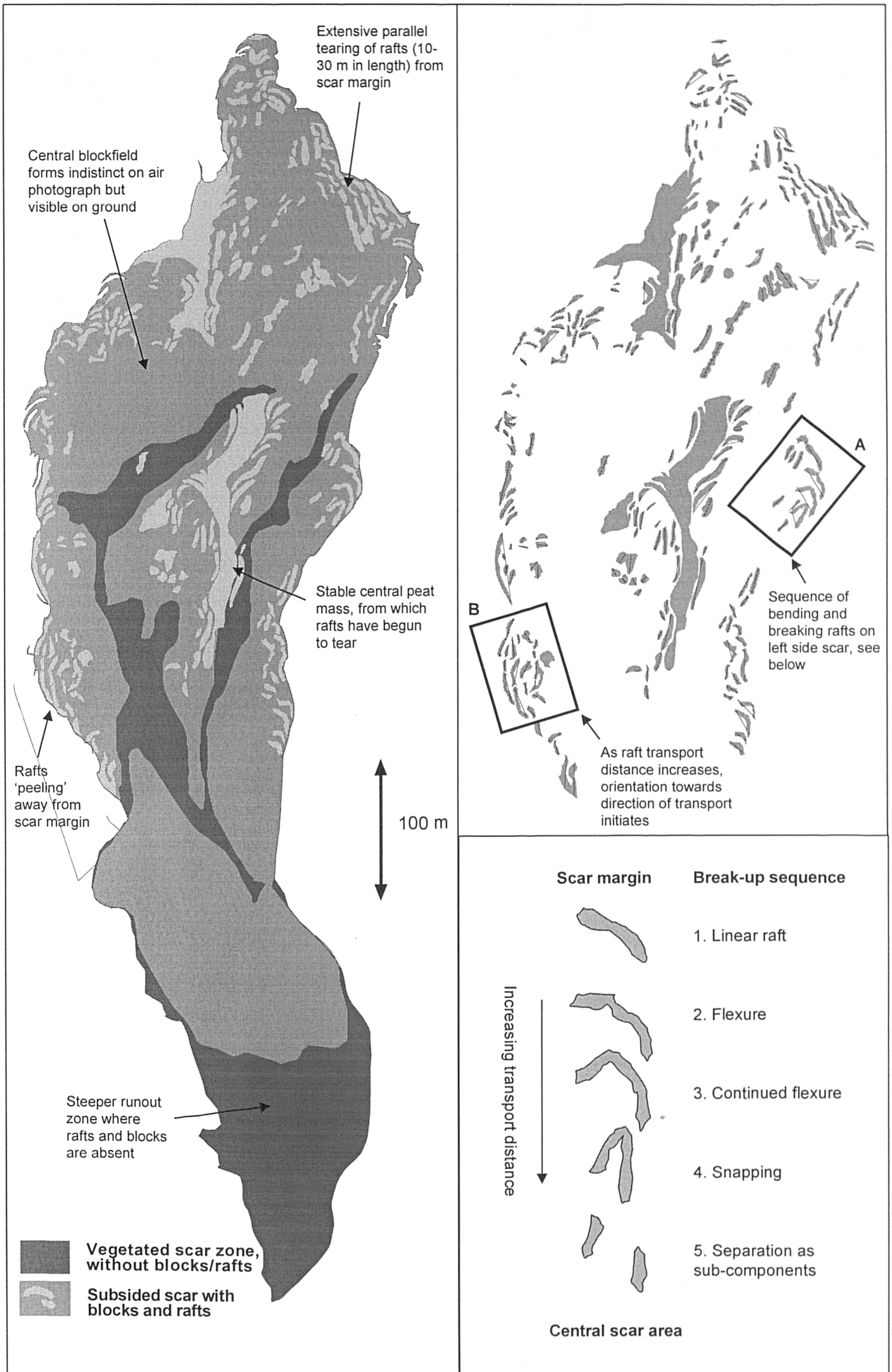


Figure 8.3. Bog burst morphology at the Glendun failure. a) sedimentary zones with isolated stable peat masses; b) rafts and long axes - parallel and concentric raft and tear patterns clearly visible at scar periphery; c) hypothesised peat mass break-up sequence from raft sub-population (boxed in 'A') - tendency towards elongate forms on detachment governs mode of break-up, based on flexure and snapping around raft centroid.

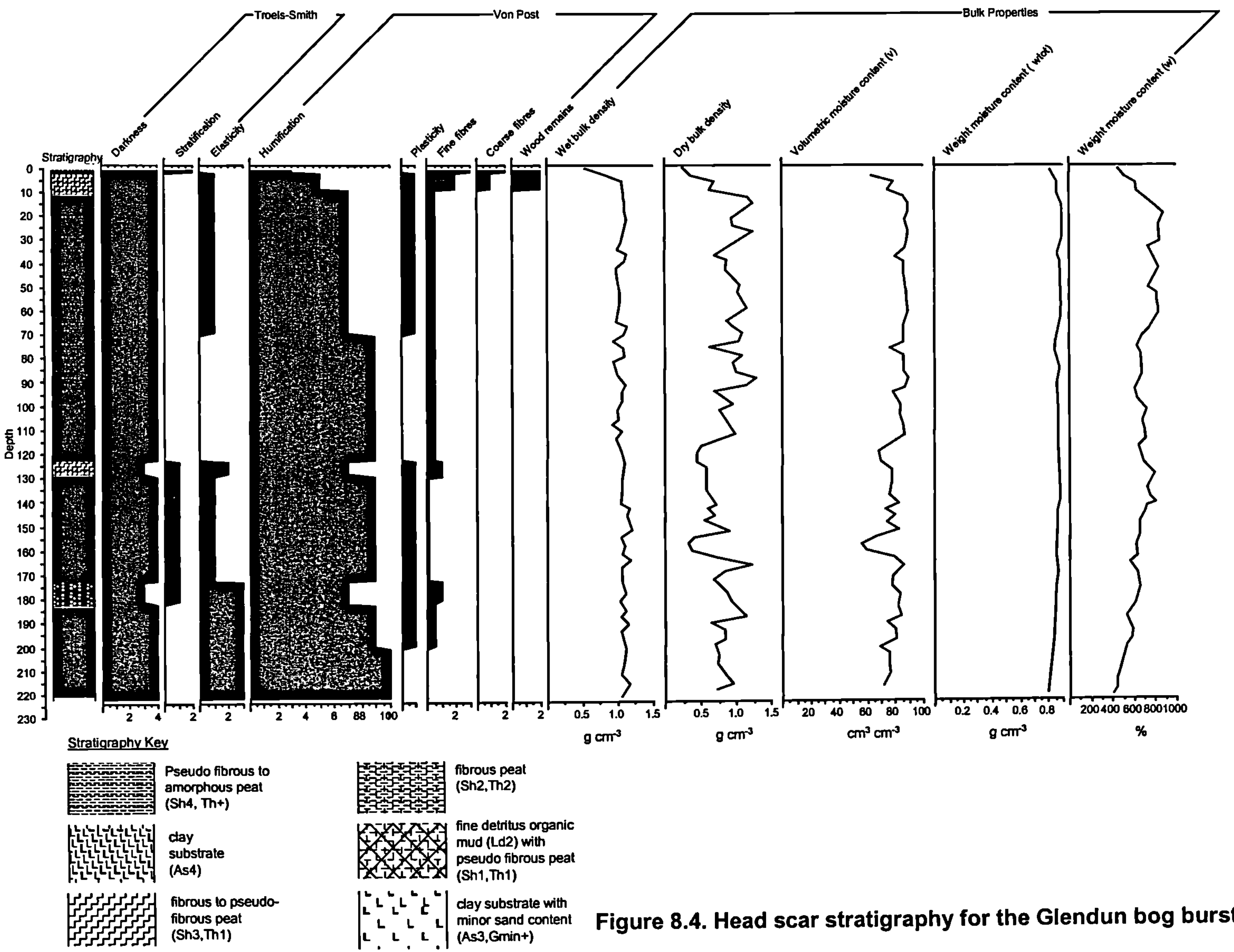


Figure 8.4. Head scar stratigraphy for the Glendun bog burst

Figure 8.5. Features of Irish peat mass movement sites and material characteristics: a) Glendun sampling site; b) Glendun bog burst morphology in foreground, sample point arrowed; c) twin scars of Cuilcagh failure, with bog burst morphology in background and slide morphology in foreground, location of photograph d) arrowed; d) dense surface clast armouring of substrate.

While the degree of humification has often (Hemingway and Sledge, 1941-46; Mitchell, 1938; Tomlinson, 1981; Wilson *et al.*, 1996) been cited as a means of differentiating a two-layer peat system in bog bursts, there is little support for such a material discontinuity in this core sample. Humification values are similar to those at Nein Head 2 and Hart Hope, though the peat profile is far more uniform than at either of these sites.

Von Post wet bulk density and dry bulk density for peat samples from Glendun are plotted against values for peat slide peat samples in Figure 8.6a. Similarly, volumetric moisture content is plotted against gravimetric moisture content in Figure 8.6b. The relative density plots indicate consistent wet bulk density within the bog burst range, but variable dry bulk density. The implication of this is that for a given sample, the percentage of the total volume comprised of water or peat is highly variable. Figure 8.6b shows consistent moisture contents, clustered at the wetter end of all the sampled peat set, which supports the idea that it is the quantity of peat solid that is most variable within the ranges shown. This variability might indicate the presence of micro-scale pockets of peat with very little coherent structure and hence increased likelihood of liquefaction. However, no discernible difference in handling consistency or moisture content was found between the Glendun and North Pennine sites.

Extensive drainage indicated by the regularly and closely spaced grips (Figure 8.1) may have caused drainage changes in the peat mass since cutting. The presence of a recent burst near the north west end of Glendun suggests that the slope has been, or continues to be unstable. It is possible that the material left in situ does not reflect that exported during failure, which is the reason for its stability on the slope in question. Hence, the materials sampled may not be indicative of those which failed. An interesting landscape contextual factor relating to this, and some other bursts (Geevagh/Straduff in particular) is the proximity of the failures to the summits of their respective hillslopes. This slope position limits the extent to which hydrological head may develop and promote instability, as well as reducing the extent to which the failed material was loaded from above.

The origins and role of slurried peat may differ between peat slides and bog burst sites. This has implications for fluidity of failure and the mechanism of solid deposit arrest. At peat slides, morphological evidence supports a wear-dependent mode of arrest, with blocks transported on their own remoulded basal material. Increased friction results from wear of the block base to the upper fibrous layer, causing cessation of transport (Chapter 5, section 5.4.4). At bog bursts, it is hypothesised that slurry or fluid peat exists before failure. Therefore, dissipation of slurry once transport has initiated depends upon dispersion by flow of material from the disturbance zone. Loss of basal material in this way may be particularly rapid, given increased velocity associated with increased fluidity. Site morphological evidence that would clarify sequences of deposition and the nature of process activity would include extent of subsidence (a proxy for slurry depth), and mass balance from disturbance head to toe. A similar mass balance approach has been used by Feldmeyer-Christe (1995) to examine bog burst morphology in a Scandinavian example. The implication of morphological variability between bursts and slides (of which evidence has been provided) is that baseline conditions for recovery will differ between the two event types. This is considered in the next section.

8.4 Bog burst recovery

Evidence of recovery is provided by the extent to which morphology is preserved at the burst sites. Substrate exposure is bare (to absent) within burst disturbance areas. As a result, vegetation colonisation will initiate on bare peat surfaces, rather than mineral material. Figure 3.25 suggested that vegetation species recorded at burst sites reflected wetter peat communities at more advanced stages of succession. The presence of a broken peat cover and proximity of intact species communities in raft-tear-raft sequences may encourage rapid recovery. A study of a Swiss bog burst by Feldmeyer-Christe (1995) suggests that the key ecological changes in the aftermath of failure involved drying of raft tops, and associated change in species, including the loss of *Sphagnum*.

From the air, morphological features (such as rafts and tears) are clearly visible for many years after failure. The distinct crescent shaped peat masses (highlighted earlier in Figure 8.1a) illustrate regularity of surface texture absent in intact peat. However, on the ground, older failures become more difficult to locate. Two adjacent sites at Straduff (Geevagh) from 1945 and 1984 exhibited very similar morphology, but differing degrees of recovery. The more recent failure has retained bare peat surfaces and, in places, drainage has incised into the peat between rafts, exposing substrate (e.g. Figure 8.6e). The older failure is visible only by alternating patches of *Eriophorum/Sphagnum*, and aquatic species inhabiting shallow pools in the former tears. Rafts tops showed *Sphagnum* cover and *Eriophorum* is present in the ponded former tears. Old bog burst sites are treacherous underfoot in their raft-tear morphology, where vegetation cover conceals the quaginess of the sites. Further data

Figure 8.6a. Wet and dry bulk density for slide peat layers and Glendun peat layer

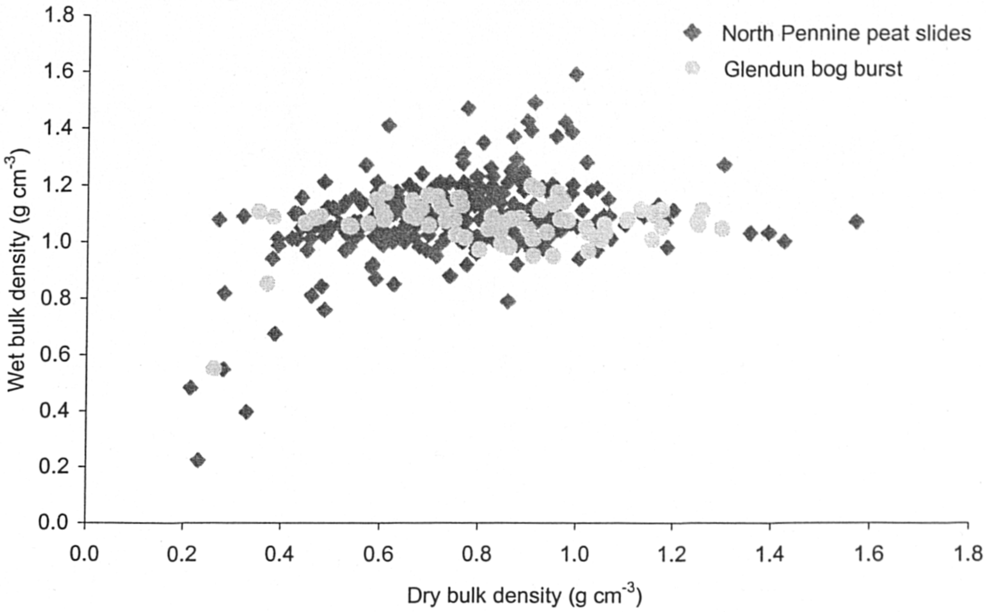
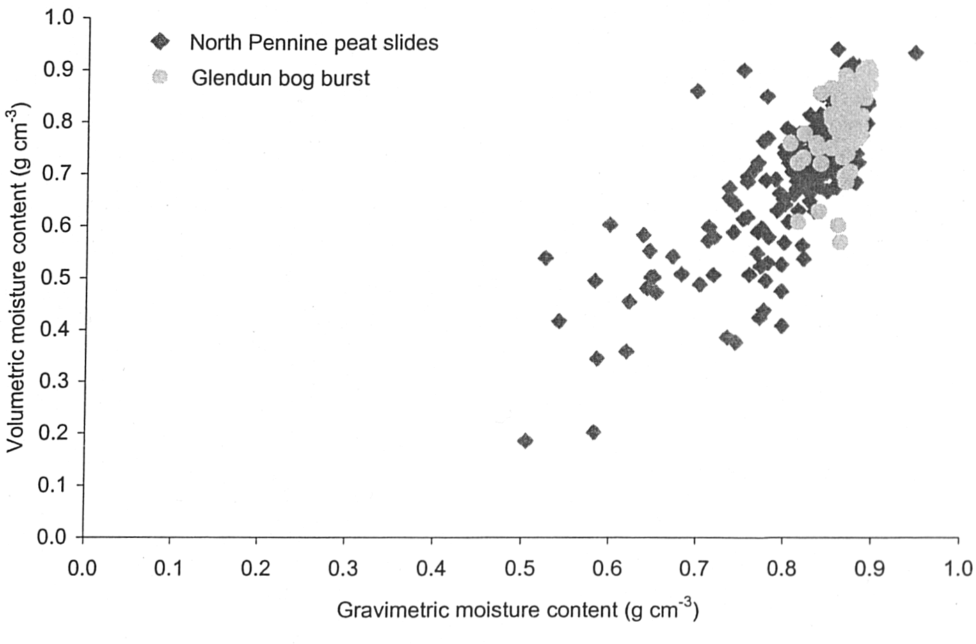


Figure 8.6b. Volumetric and gravimetric moisture contents for slide peat samples and Glendun samples



is required to examine the balance between degradation caused by water drainage, and recovery caused by revegetation of tear-pools. It is possible that in the long-term, bog burst sites may re-activate (e.g. Kinahan, 1897; Clough, 1897), given the often minimal transport distances experienced in failure.

8.5 Bog bursts and peat slides reconsidered

The two-phase system for classification of bog burst and peat slide form and process may now be reconsidered in the light of evidence of both event types. Bursts and slides have been shown to share morphological units (blocks, rafts, slurried peat) but the arrangement of these units differs. Slides exhibit largely excavated scars, with platy solid peat masses comprising up to 50% of the displaced material. These rafts decline in size and number down-slope, with blocky and slurried deposit increasingly dominant. The morphological-conceptual model in Chapter 5 describes the sedimentary zones that characterise this process activity.

Bog bursts are characterised by a sunken, amphitheatre shaped disturbance zone, in which the boundary between 'scar' and undisturbed peat is not clearly defined. The larger solid masses are crescentic and elongate, and decrease in size and number with increasing transport distance. A size-distance gradient is often visible from the scar margin to the centre of the disturbance area, even though transport distances are minimal. The most significant difference between bursts and slides is the lack of complete excavation of the upper disturbance/scar areas. The convergence of form towards flowing blocky deposit in the lower reaches of each failure type conforms with the simple conceptual model in Figure 2.13.

While morphology is distinct at either morphological extreme, there is evidence to support a gradation of form. Two failures, Feldon Burn (1990) in the North Pennines, and Cuilcagh (2000) in Co. Fermanagh (Dykes and Kirk, 2001) illustrate combinations of both burst and slide morphology. In both cases, dual scar areas are found with a largely excavated slide scar over locally steeper relief, and a rafted and choked disturbance area on a shallower slope. The difference between the two disturbance/scar types is clearly visible on the oblique air photo of Feldon Burn in Figure 8.7a. Ground photographs at Cuilcagh show a similar arrangement of morphology. In the case of Feldon Burn, data from Chapter 7 suggested that the failed peat masses occupied drainage lines - perhaps flushes, and it is possible that subsurface, fluid material was present. The landscape context for Cuilcagh is unknown.

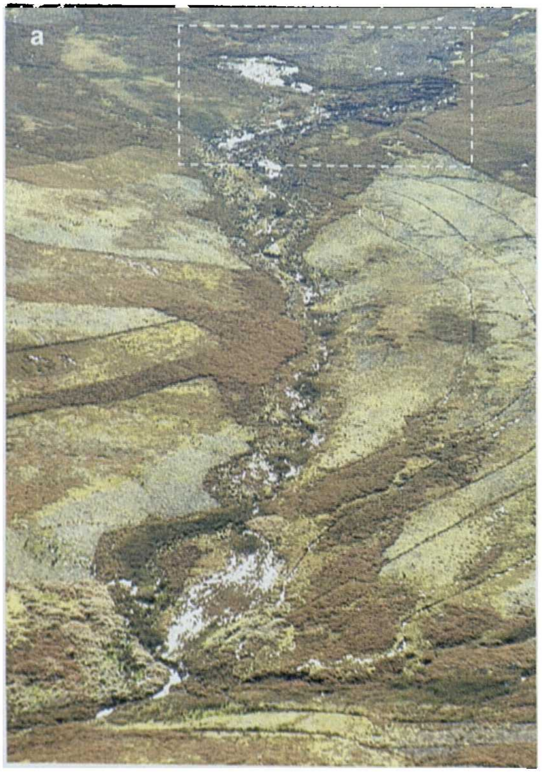


Figure 8.7. Intermediate forms. a and b) Feldon Burn (1990) whole scar and head scar - excavated scar morphology visible on left of blow-up, and concentric rafted debris on right of blow-up, the latter occurring in a drainage line, and the former over slightly steeper ground; c) the Cuilcagh (2000) failure in Co. Fermanagh. Crescentic rafting visible on left hand side below confluence of excavated scar on right bank side. Elevated position of 'slide' morphology relative to 'bog burst' morphology clearly visible.

The presence of intermediate or composite 'slide + burst' sites suggest that burst and slide morphology may occur in proximal materials that are likely to have formed over similar timescales. As yet, discrete and separate bog bursts and peat slides have not been recorded adjacent to one another in peat blanket areas.

CHAPTER NINE SUMMARY AND CONCLUSIONS

9.0 Thesis overview

The aim of this thesis has been to provide a geomorphological assessment of peat slide events, based on characterisation of form, mechanisms and post-failure development. The main objectives were to:

i) Synthesise previously published information on peat mass movements.

ii) Refine the classification of peat slide features through characterisation of morphology and failure mechanism.

iii) Establish the basis for distinguishing between peat slide features and bog burst features.

iv) Assess the geomorphological significance of peat slide features in blanket peat environments.

This chapter provides a summary of the key findings, and contextualises them against wider issues in the development of blanket peat regions, including internal and external controls on stability. The final section makes suggestions for extension to this research work.

9.1 Evaluation of data synthesis

Previously published information concerning peat mass movements was collated in Chapter 2, and analysed quantitatively in Chapter 3. Examination of previous work highlighted research gaps, the resolution of which formed the basis of hypotheses presented in section 3.3. The key findings from the development of the database can be summarised as follows.

The global distribution of peat failures indicates a concentration in UK and Irish mires (Figures 2.2 and 2.3), with only scattered examples from other peatland environments (Table 2.1). There are no clear reasons for this, and their significance should not be over-emphasised. Much of the analysis in this thesis reflects the characteristics of UK and Irish examples, and care must be taken in applying findings from this work to features in non-UK and Irish peat environments.

Peat failures are features occurring in peat deposits of depths greater than 0.5 m (Figure 3.16). While some failures have been reported in shallower peats, these are often located near the blanket margins, usually at the organic-mineral soil transition. These failures are similar in morphology to debris slides and debris flows of mineral soils, with only thin organic horizons at the soil surface (peaty-soil failures). Peat blocks are usually less pronounced and peat rafts are absent. Variability internationally in the minimum depth of organic matter used to define 'peat' may explain the inclusion of some of these failures in the reported population of peat failures. However, accounts of such features are valuable in indicating how peat failures may be morphologically similar regardless of spatial location within the peat blanket.

Accounts of peat failures fall into those described as bog bursts (generally the earliest examples), and those described as peat slides (mainly the later examples). In the absence of established landslide classification frameworks, such as that of Varnes (1978), Hutchinson (1977) and Crozier (1973), the excavated scars of peat slides with exposed substrate were noted primarily by the absence of fluidised material (e.g. Mitchell, 1938). The use of these classifications later saw peat slides considered as translational slide failures, separated from bog bursts as liquefied flow failures. The noticeable increase in reported peat slides in recent decades (particularly since 1960; Figure 3.9) does not appear to reflect a favouritism for 'slide' terminology, but a genuine increase in awareness of the features, and possibly an increase in frequency of occurrence.

The two dominant failure types are clearly distinguished by their topographic settings, with slides occurring on slopes in excess of 5° and at altitudes of over 300 m, with bursts on slopes under 7° and at altitudes below 500 m (Figure 3.14). The differences in slope correspond to the differing ranges of peat depth in which slides and bursts are located. Slides occur predominantly in peat between 0.5 and 1.5 m in depth, with bursts found through the full range of recorded bog depths (up to and in excess of 5 m deep). Peat slides occur predominantly on both concave slopes where slope angles are low, and on convex slopes where slope angles are greater. The latter are associated with blanket peat margin locations, associated with relatively steep convex valley sides, while the former are associated with internal failures within the blanket peat areas of locally variable topography (section 3.2.3). Peat slides have been shown to occur in spatial (down to the hillslope scale) and temporal clusters, whilst bursts generally occur in isolation. Only on rare occasions is more than one burst to be found on the same hillslope.

Morphological description throughout the 20th century has been shown to be particularly thorough, with morphological maps frequently used to portray a complex juxtaposition of deposit components, particularly in bog bursts. Statistically-based analysis of slide and burst morphological components (Figures 3.8, 3.11, 3.12) indicate that although slide scars are consistently more excavated than those of bog bursts, deposit forms cover a similar size range, and hence break up of the peat surface once movement has initiated may be governed by similar local processes (tensional splitting). No attempts have been made prior to this study to provide a morphological criteria for distinguishing slide and burst failures, as outlined in section 3.3. As a result, the research in Chapter 4 has focused upon morphological criteria for the definition of peat slide events.

The initiation mechanisms for movement have been poorly investigated in past studies (section 2.3.1). A greater proportion of slides than bursts are associated with unusually intense rainstorms, but climatic data were not sufficiently detailed to examine threshold intensities or rainfall quantities. Prior research has attempted to utilise geotechnical approaches to failure initiation, but has focused on failure within the substrate rather than within the peat mass or at its substrate contact (Carling, 1986; Dykes and Kirk, 2001). Consideration of runout has only been descriptive, despite the widespread morphological evidence in the aftermath of failure, including rafts, blocks, slurry and levees. In response to the limited previous research, an exploratory approach to slide sediment dynamics has been developed in Chapter 5. Chapter 6 investigates the material basis for the observed morphological patterns.

There has been a scarcity of studies concerning the post-failure recovery of peat mass movement sites, with the limited number of examples considering individual sites within a few years of failure. The importance of rate of recovery in disguising the presence of former, unidentified failures in the landscape has also been noted (section 3.3). Chapter 7 presents the results of a pilot study of recovery of peat slide scars, utilising a range of techniques applied to slide scar studies in other environments.

Although most of this thesis focuses on peat slide failures, the synthesis provided by both the database and literature review provides a basis on which to investigate the hypothesised differences between peat slides and bog bursts. Chapter 8 provides a comparative case study of a typical bog burst feature, further clarifying similarities and differences between the two failure types.

9.2 Summary of empirical research

9.2.1 Peat slide morphology

Peat slide form has been assessed for a set of regional failures in the North Pennines, spanning more than 60 years. Scar and deposit morphology were mapped using aerial photographs. Smaller deposits were surveyed using a Total Station theodolite and calibrated with features visible on the aerial photographs. The suite of failures investigated in the North Pennines demonstrated the full range of topographic styles established in the data base, with examples found within and near the margins of the peat blanket (Figure 4.4) and on a range of convex, concave and rectilinear slopes (Figure 4.3). None of the failures surveyed fell within the peaty-soil failure category identified in the previous section.

Scar and deposit dimensions in the North Pennines are highly variable, with a range of scar morphometries identified (Figures 4.6 to 4.8). Scars ranged from highly elongate features (such as Hart Hope and Feldon Burn) with scar lengths in excess of 300 m, to obloid excavated areas with crescentic scar heads (Iron Band, Nein Head 3, Middlehope, Meldon Hill East and West, Benty Hill). There are a number of intermediate forms of significant length and breadth (Nein Head 2 and Langdon Head) and some failures in which much of the failed peat has restabilised as large and coherent masses within a few metres of movement (Benty Hill, Langdon Head and West Grain) (Figures 4.13 and 4.14). Comparison of these scars with previously published examples in Ireland suggests some similarity between failures across the different regions, and hence a commonality of form across blanket peat areas in the UK and Ireland.

Detailed mapping of rafts and blocks has established that many of the coherent re-stabilised peat forms can be visually traced back to their points of origin on the basis of shape. In deposition, rafts exhibit ruptures in the form of tears and peripheral cracking. Ruptures through the centres of the rafts are associated with a process of fracturing responsible for the gradual diminution of larger peat masses into successively smaller debris. Diminution of transported peat masses has been shown to increase with increasing travel distance. Rupture, in the form of tension splitting and snapping, has been shown to be associated with the peat mounting scar margins and the impact with other rafts. Rafts show a characteristic size determined by spacing of ruptures, which is generally greater than the population of block volumes (Figure 4.16).

The smallest coherent fraction is defined as the block fraction, for which a characteristic form ratio of 1.6 has been established. The spatial distribution of block rounding exhibits little clear pattern, although there appears to be a tendency towards roundness in distal deposits. This is interpreted as indicative of continual splitting of larger peat units into progressively smaller units, with fresh and angular faces found throughout the length of the deposit track. The slurry component is largely absent from all but the most recent failure (Coldcleugh Head). Here, the slurry has been significantly reworked by subaerial weathering. Photographic evidence for a number of failures indicates that the slurry appears to be composed of larger 'peds' of peat (up to a few decimetres in long axis) within an amorphous matrix. The same photographs suggest that this slurry is largely found outside the scar areas and surrounding (but rarely overtopping) the larger peat deposits.

Taken collectively, raft, block and slurry evidence has been used to formalise a morphological-conceptual model of peat slide scar and deposits (Figure 4.24), based on the more characteristic obloid-crescentic scar form described previously. The deposits have been zoned according to a dominance of rafting in the upper track and blocks and slurry in the lower track. Deposit tracks generally exhibit significant extension, but little lateral spreading (agreeing with data presented in Chapter 3). A number of slides are directly coupled to local channel networks, and depositional evidence is limited.

9.2.2 Event sediment dynamics

Spatial variability in peat slide deposition has been examined using a zoned approach (Chapter 5). Block attributes are related to distance travelled through a series of 30 m slope length zones. Block size declines downslope, with block diminution mainly a function of reducing block area rather than block depth. This suggests that break up of the moving peat occurs mainly by vertical fracturing, rather than basal abrasion. In the failures with elongate tracks (Nein Head 2 and Nein Head 3), block numbers and block volumes, peak and trough in alternate deposit zones, suggesting alternating compression and extension, and local congestion through the total track length.

Observations of block orientation, dip and roundness suggest that blocks retain their form over small transport distances, aligning parallel to local break-away faces (such as scar margins or rafts). With increasing transport distance, long axis orientations are shown to be preferentially aligned downslope through channelised sections of the track. In high-density block zones, collision of blocks and a tendency towards local compression give rise to orientations normal to the slope. Apart from these locations, orientations are usually oblique to the transport direction, and can largely be regarded as random. A combination of dimension and vector information suggests that peat slide sediments rapidly disperse following initial movement. Rafted peat degenerates quickly, through a sub-component stage and into blocks. The absence of blocks with equivalent b and c axes suggests that should blocks become capable of rolling (having acquired rod-to-sphere dimensions), they rapidly disintegrate. It is likely that the peat peds are the final coherent stage of peat sediment prior to the highly remoulded and fluidised slurry, and the threshold size below which all material is lost to wash and fluvial transport.

The relative volumetric significance of the raft, block and slurry components has been evaluated in a sediment budget. Given the premise that rafts must slide, blocks may slide or roll, and slurry must flow, the relative proportions of each deposit type at any point on the slope can be used to establish the dominant geomorphic process activity with increasing slope distance from the scar head. Rafts, where present, dominate the upper slopes at peat slide sites, with a rapid but short-lived rise in the volumetric significance of peat blocks. Thereafter, slurried deposit represents the main mode of sediment transport, with blocks decreasing in importance and rafts absent. The absence of slurry from most surveyed sites suggests that a significant proportion of depositional information is not available for the interpretation of sediment dynamics at peat slides. It also suggests that the interpretation of sliding as the major movement mechanism at peat slides is unfounded, and that sliding is dominant only in the initial stages of movement. The progression from sliding to debris flow has been formalised in a process-based model of peat slide runout (Figure 5.19). The presence of highly humified basal layers at many of the sites suggests that both abrasion and block fragmentation contribute to the generation of slurry. A debris flow, with surging behaviour is a more appropriate representation of movement mechanism thereafter. When considered in total, rafts, blocks and slurry accounted for displaced volumes generally exceeding 4000 m^3. Although relatively large for active landslides in the UK, they still fall well below the volumes mobilised in the largest of inland and coastal examples which may involve several million cubic metres of material (Jones and Lee, 1994).

9.2.3 Material characteristics of peat blankets experiencing mass movement

Material characteristics of the peat and substrate immediately adjacent to the failed peat at each site have been examined using stratigraphic and geotechnical techniques. Peat slide stratigraphy comprises three main units within the peat, two units within the substrate and a unit comprising the peat-substrate contact zone. Bulk properties and data pertaining to fibre content, elasticity and texture are used to characterise each layer.

The peat mass itself is generally divided in two on the basis of fibre content and decomposition. A thin upper layer corresponding to the hydrologically active acrotelm, and a lower, much thicker layer comprising the permanently waterlogged catotelm. The main significance of the acrotelm is the restraining characteristics of the fibre mat, and its irregular shear strength (contingent upon vegetation type). Local patchiness in vegetation gives rise to variable surface tensile strength and hence greater or lesser tendencies towards coherence of a mobilised peat mass. The lower peat is subdivided into pseudo-fibrous deposit overlying a pseudo-fibrous to amorphous peat. While the former exhibits localised fibre bundles associated with more decomposition-resistant species, and hence some tensile strength, the latter is largely without fibres suggesting low-to-absent tensile strength. In addition, the lower catotelm peat frequently contains wood fragments which appear to act as loci for fracture given significant application of stress. The amorphous nature of this basal peat provides a source for slurry during wear of blocks and rafts in transport.

The nature of the 'peat-substrate contact' layer varies according to the presence or absence of transition material. Such material has been shown to comprise a predominantly peaty matrix with a minor clay component, and represents a relatively strong layer in the peat-substrate profile. However, a weaker contact results where a clean interface between highly humified peat and substrate is found. Here, the peat weakly adheres to the underlying substrate and shear failure at the contact is more likely. The substrate itself may be subdivided into two layers. The upper unit comprises remoulded and locally soft, fractured and ductile silty clay, that prior to the onset of peat development has probably been reworked by post-glacial subaerial weathering and erosion. The lower unit comprises a stiffer, more stable and overconsolidated till of higher shear strength and high cohesion.

On the basis of shear strength testing and bulk property information, envelopes of material strength have been constructed for the full peat-substrate profile (Figure 6.22). Under 'drained' conditions, or long term deformation and continued dissipation of pore-water pressures, both the amorphous peat and remoulded substrate may be regarded as predominantly stable over slopes typical of the North Pennines. Under undrained conditions, or where basal pore-water pressures are significantly increased, the angle of internal friction component of shear strength has been shown to be significantly lower for the contact and remoulded units than the other units tested. Slopes in excess of 5° may be regarded as unstable. This compares well with the range of slopes over which peat slides occur, all of which are in excess of 5°. A combination of low angle of internal friction and cohesion within the contact zone suggest it as the most likely failure plane. The presence of pipes and lines of seepage is restricted mainly to the points of contact between the different units. However, pipe dimensions and potential discharges are relatively limited, and do not support preferential supply of water to the base of the peat mass over any other layer within it. Hypothesised failure mechanisms have been re-evaluated in the light of this information, and through a process of elimination, shear failure has been established as the likeliest initiation mechanism for failure at peat slide sites.

9.2.4 Comparison of peat slide and bog burst characteristics

The differences between peat slides and bog bursts have been examined, on the basis of morphological, mechanistic and recovery criteria developed from the North Pennine peat slide population. A bog burst case study of the Glendun (1963) failure has been used, and taken to be representative of other bog burst features on the basis of maps and evidence presented in Chapters 2 and 3 (Figure 2.8).

The bog burst case study indicates that many of the larger mobilised peat masses are elongate, contrasting with the rectangular slabs associated with peat slides. However, these large crescentic rafts are generally confined to the main scar area, decreasing in size with increasing distance from the scar margin. As such, they indicate the relatively minor excavation of bog burst disturbance areas as a whole. In the lower tracks of bog bursts, field survey suggests that the dislocated peat forms are similar in size and shape to peat slide blocks, and that some convergence of process activity exists after initiation. A material basis for differences in peat characteristics between bog burst and peat slide sites has not been established, although material sampled from the Glendun site suggests slightly wetter and less dense material than at the North Pennine peat slide sites, with slightly greater humification at depth. The differing baseline conditions for revegetation, as a direct function of the low scar excavation, suggest a shorter timescale for recovery of bog burst sites.

9.2.5 Recovery of peat slide scars and their geomorphological significance

The recovery of peat slide scars has been examined using a nested approach across scars of differing age. Soil, vegetation and geomorphic development have been used to formalise a model of peat slide recovery. This model considers scar development from the immediate aftermath of failure on a scale up to >1000a (Figure 7.18). Characteristic geomorphological, ecological and pedological activity may be associated with each recovery phase.

In the years immediately subsequent to failure, geomorphological activity peaks with the development of shallow surface drainage and a progression to surface incision by rilling. In the lower and/or steeper parts of longer scars, gullying develops and progresses upslope through head-cutting, and laterally through localised bank failure. Revegetation and surface modification of substrate characteristics are minimal in this earliest stage of recovery, and the overall balance of site activity is biased towards continuing degradation rather than recovery.

After nearly a decade, vegetation colonisation has begun, with pocking of the scar surface by grasses and rushes, but greater development of rilling. The breakdown of the substrate surface structure by weathering and erosion aids this process. Local deposition of washed sediments forms seasonally waterlogged patches of scar in which rush growth concentrates. In addition, the continual development of waterlogged margins adjacent to the scar edges, fed by drainage from their free faces, leads to rush growth at these locations. Sediment export from the scar into local drainage networks continues where gullies in the lower slopes become coupled.

Through the following decades, vegetation becomes fully established, initially through the amelioration of the scar surface by the hardier grasses and rushes. This preparation of the surface has a number of effects. Firstly, the development of a substrate surface more amenable to species with deeper rooting requirements, and hence the opportunity for greater species diversity. Secondly, a reduction in runoff from the scar surface, leading to a change in the moisture balance of the scar towards wetter conditions. Finally, a reduction in on-scar geomorphological activity. In combination with these changes, nutrient cycling is shown to increase through this period, suggesting a more fully active and recovering biogeomorphological system.

Subsequent development sees a change to more acid surface conditions with increased waterlogging, and the development of an organic soil beneath the surface mat of vegetation. In addition, more characteristic bog moss species, such as *Polytrichum* and *Sphagnum* develop, and species diversity declines. At this point, the scar surface can be considered as 'recovered' with respect to its surroundings and its ecological and geomorphological function. Only the re-initiation of peat-accumulation, dependent primarily on climate, would allow a return to a surface fully integrated with its surroundings.

An extension of Chapter 5's sediment budget approach, to include the full timescale of slide scar geomorphic activity reveals that in some cases, post-failure activity at larger slide scars may be nearly as significant as some of the smaller slide events. Simulations using the Revised Universal Soil Loss Equation for the twelve months following failure suggest surface lowering of up to a few centimetres for the exposed substrates, as a consequence of rill and interrill erosion alone. Where deeper drainage networks are active, such as headcutting channels, several hundred tons of material may be mobilised, and post-failure activity may be significant. The development of such networks is largely a function of scar morphometry, with long, linear scars favouring concentration of drainage.

9.3 Synthesis of empirical research with previous findings

This section considers the importance of peat mass movements in the context of other processes operating in blanket mire environments. The main erosive agent operating in peat blanket environments is gullying (Bower, 1961; Tallis, 1998). Wishart and Warburton (2001) have examined the spatial relationship between gullying and mass movement for the Cheviot Hills, at the north end of the Pennine chain. Anastomosing, dendritic and linear gully patterns were altitudinally distinct, with a large peat slide located at the lower altitude limit of linear gullying (approximately 450 - 500 m). In this thesis, gullying was generally noted as absent on the slopes adjacent to those affected by peat failures, though several examples were cited in which slide scars were found beneath established gully systems. Wishart and Warburton (2001) suggest that gullies may act as erosion nucleii from which further erosion may develop. Peat slides also exhibit further erosive activity in their aftermaths, although there is little evidence (with the exception of Hart Hope) to support the propagation of gullying associated with this activity beyond the confines of the original scar. The assertion by Tallis (1985) that peat slides may initiate gullying, particularly slides near the peat margin, is not supported by this work. It should be noted at this stage, that the absence of slide scars in gullied areas generally may indicate that former scars have been effaced by subsequent gullying activity. The process significance of peat failures as compared with gullying is minimal if considered in terms of sediment yields. Over the timescale during which peat slides have been reported in the North Pennines, slide events and slide scar processes together account for 3% of the total sediment delivered to fluvial networks, and 7.8% of the sediment mobilised. Given that the North Pennine 'cluster' is the largest regional set of slide failures, the significance of peat slides in other regions is likely to be much less.

The temporal distribution of peat mass movements may also be compared with that of gullying. Peat failures have been recorded over the same period that gullying has been in operation, with the earliest failure reported at Chat Moss in 1526 (Crofton, 1802). Although there is some disagreement concerning the time of onset of gullying, most major gully complexes have been suggested as initiating between 500 and 200 years ago (e.g. Bower, 1960; Labadz *et al*, 1991; Tallis, 1998; Wishart and Warburton, 2001). Both slides and bursts have been continually active over the last 300 years (Figure 3.9, from which Chat Moss is excluded). The rate of bog burst occurrence has changed little through this period, while peat slides have increased markedly in number in the last 25 years. There are both conceptual and practical implications relating to these trends. In practical terms, any increase in peat mass movement occurrence may affect water colour and water quality in coupled stream systems, as well as disrupting the hydrological and ecological function of the peat blanket, removing a deposit of acknowledged landscape value, and producing a negative visual impact in localities traditionally classified as Areas of Outstanding Natural Beauty. The implications of the differing trends for blanket stability are harder to quantify.

Conditions suitable to the occurrence of bog bursts may have changed little in the last 300 years, and conditions suitable to the occurrence of peat slides may have increased in the last three decades. It is also possible that reports of peat slides and bog bursts do not represent the true failure populations, and that this is the reason for the differing frequencies. Given the perceived variability in onset of peat development in the uplands of the UK and Ireland (Burton, 1996; Tallis, 1998), and across the globe generally (e.g. Rabassa *et al.*, 1996; Steffens, 1996), it is unlikely that either feature exists as a 'natural endpoint' to peat accumulation (Conway, 1954). The fact that most failures are found in areas in which gullying is not prevalent, suggests that peat mass movement is not related to the latter erosion process, other than in its effects of peat export from blanket mires. Both failure types pre-date significant human-induced interference with blanket mire environments, although it is possible that broad scale hydrological changes associated with increased drainage may exert a destabilising effect on the peat blanket as a whole (Heathwaite, 1993). Heathwaite (1993) cites Edwards *et al.* (1987), in suggesting that recent increases in temperature associated with climate change may increase the production of humic acids. These may act upon the substrate beneath increasing instability in peatland areas. The presence of locally soft clays beneath intact blanket (section 6.2.1) may support the idea of lenses of weakened substrate material. Such changes would presumably directly affect only peat slides, given that bog bursts appear not to incorporate the substrate in failure.

The rise in number of peat slides in the last thirty years may be associated with a changing climate, the manifestations of which have been associated with a general tendency towards slope instability (Jones, 1993). Higher winter rainfall, increased likelihood of summer droughts, and increased summer storm activity all support an increased incidence of rainfall triggered peat slides. Droughts have already been implicated in the generation of deep cracking, which acts as a pathway for water to the peat at depth (Bower, 1960). Summer storms have been directly associated with most of the failures cited in the North Pennines (Crisp *et al.*, 1964; Carling, 1986; Johnson, 1992), and it appears mainly to be storms of exceptional intensity (such as cloudbursts; Hemingway and Sledge, 1941-45) that are responsible. Increased winter rainfall may increase the extent to which the upper peat is saturated, increasing the overall mass of peat overlying substrate, and potentially encouraging failure. The potential effects of climate change are not clear cut however. Increased temperatures may also result in changes to the surface vegetation of blanket mires. It is possible that with a decline in moss species and an increase in rooting plants, the surface mat of peat areas may provide a stronger restraining influence than previously, reducing the tendency towards failure.

This thesis has demonstrated that peat slide failures are distinctive and locally significant geomorphological events, whose effects persevere in the landscape on a human timescale, but which are transient in a timeframe of peat accumulation. Both peat slides and bog bursts are under-recognised as contemporary forms of active slope instability outside the case studies that have typically dominated their research. Peat mass movements are fascinating geomorphological features, and pose a number of interesting research questions, but they are relatively insignificant in the wider functioning of peat areas. However, a pronounced increase in frequency of either slides or bursts might require their occurrence to be taken more seriously in the context of upland catchment management. The final section considers further research opportunities that would complement the research presented in this thesis.

9.4 Recommendations for further research

A number of avenues of further research will extend the approaches and techniques used in this study:

1. **Extension of the Peat Mass Movement Database and site-by-site clarification of attributes.** The continued occurrence of peat mass movements should be logged and recorded within the database described in Chapter 3. This would allow an improved understanding of both magnitude and frequency, and allow the temporal trends discussed in this study to be evaluated in the light of continued failures. Requests for information regarding unpublished failures have yielded some database entries during the production of this thesis. The last known failure to have occurred in the North Pennines was that at Coldcleugh Head in 1998.

   Many failures have been published in less detail than they were surveyed in the field. Many of the publishing authors are still research active, and hence it may be possible to expand on the information available on a site-by-site basis. Even if this is limited to the distribution of database sheets and guides (Figure 3.3; Appendix 1), the quality of the data set as a whole may be improved.

2. **Survey of new peat slides in the immediate aftermath of their occurrence.** The main morphological limitations of this study result predominantly from the lag time between failure occurrence and site survey. The nature and significance of slurry cannot be determined adequately without rapid assessment of site conditions, preferably without extensive modification of deposit by subsequent climatic events.

3. **Further geotechnical testing of peat and peat-substrate contact.** The geotechnical basis for the testing of both peat and material transitions/contacts has been limited by a generally poor understanding of their characteristics in the engineering literature. It is perhaps beyond the scope of a geomorphologist's remit to elucidate and clarify these aspects of material behaviour. However, it should be acknowledged that without such progress, the adoption of conventional shear-strength based slope stability approaches to failure mechanism will be conceptually and practically of limited value. In addition, residual strength testing should be conducted for all materials in future peat slide studies.

4. **Establish the effects of humic acids on the sensitivity of substrate materials.** In the long term, peat decomposition products may affect the strength of underlying clayey substrate material, mainly in the alteration of particle-to-particle attractions produced by electrical charges. This requires further investigation, preferably through long-term exposure of materials tested for shear strength to acid solutions derived from basal peat

5. **Identification of vegetative components of peat profile layers.** The assessment of peat core stratigraphy may have benefited from the identification of species composition in each identified layer. The relative composition of leaves, stems and roots may have provided greater insight into the vegetative controls on micro-scale strength. The number of cores classified stratigraphically (in excess of 100 m) made this approach impractical.

6. **Resurvey of recovery sites.** The validity of the recovery model formulated in Chapter 7 may be assessed through periodic survey of the sites described in this thesis. The techniques would require few significant modifications.

7. **Full survey of bog burst sites.** A regionally based approach to bog burst failures, using similar approaches to those described here for peat slides, would provide a greater basis for comparison of the two failure types. This would necessarily be based in Northern

Ireland (Co. Antrim) where the largest cluster of both slides and bursts is reported. However, comparison of these examples with a recent UK bog burst (Boulsworth Hill, Evans, 1993) would also be of value in elucidating why bog bursts occur primarily in Ireland, and peat slides primarily in the UK.

Appendices

Appendix 1. Glossary of terms used in peat mass movement database

Database field	Description	Units
General description section		
slide	failure with morphology corresponding to description in Chapter 2, section 2.2.1	n/a
burst	failure with morphology corresponding to description in Chapter 2, section 2.2.2	n/a
slump	small rotational failure, corresponding to neither 'slide' or 'burst' morphologies	n/a
margin	scar and deposit located as shown in Figure 3.5a	n/a
to-margin	scar and deposit located as shown in Figure 3.5b	n/a
within	scar and deposit located as shown in Figure 3.5c	n/a
discrete	single failure, with no others associated on the same hillslope	n/a
multiple	one of a number of failures occurring in the same climatic event on the same hillslope	n/a
cyclic	failure which has been active under prior climatic events	n/a
Morphological characteristics		
blocks	*small, solid peat masses, with inferred significant travel distances*	n/a
rafts	large, solid peat masses, with minor travel distance	n/a
slurry	*a mixture of structureless peat deposit with small fragments of former solid debris*	n/a
max.block size	a-, b- and c- axes of the largest solid deposit	metres
within	deposit is largely confined within the scar area	n/a
beyond	deposit is distributed beyond the scar area	n/a
to-channel	deposit has been incorporated into local channel networks	n/a
minor	peat mass displacement minor, < 50% of disturbed material transported beyond the scar	n/a
major	peat mass displacement major, > 50% of disturbed material transported beyond the scar	n/a
complete	peat mass displacement complete, >95% of disturbed material transported beyond the scar	n/a
tension cracks	narrow cracks (< 0.2 m wide) in the peat surface	n/a
tears	wide, and usually deep fissures in the peat surface (>0.2 m wide)	n/a
post-failure tc./te.	cracks or tears judged to have formed in the aftermath of failure due to subaerial weathering	n/a
max.crack depth	the greatest depth to which the deepest crack or tear extends	metres
levees/blocklines	linear arrangements of closely associated blocky deposit	n/a

continued overleaf...

Database field	Description	Units
Drainage setting		
pipes	subsurface drainage routes	n/a
max. pipe diam.	diameter of the largest pipe found at one site	metres
discrete	only one pipe found at site	n/a
multiple	more than one pipe found at site	n/a
gripping/cutting	man-made drainage features, consisting of shallow linear incisions into the peat surface	n/a
max.drain. dim.	maximum depth and width of biggest grip or cut	metres
location	location of natural and artifical drainage lines referenced to scar, according to Figure 3.6	n/a
slope/chan.coupl.	deposit has entered local watercourse	n/a
Morphometry		
aspect	orientation of scar head, as three figure bearing	degrees
altitude	altitude of scar head, to nearest 10 m	metres
length (scar)	scar dimension, as shown in Figure 3.8	metres
length (disturbance)	disturbance dimension, as shownin Figure 3.8	metres
length (deposit)	deposit dimension, as shown in Figure 3.8	metres
length (excavated)	excavated dimension, as shown in Figure 3.8	metres
width (scar)	scar dimension, *as shown in Figure* 3.8	metres
width (deposit)	deposit dimension, as shown in Figure 3.8	metres
depth (scar)	scar dimension, as shown in Figure 3.8	metres
depth (deposit)	deposit dimension, as shown in Figure 3.8	metres
slope angle (upper)	slope angle in degrees from head scar to biggest slope break over total scar length	degrees
slope angle (lower)	slope angle in degrees from biggest slope break over total scar length, to scar terminus	degrees
concave	slope with steeper upper slope angle than lower slope angle	n/a
convex	slope with steeper lower slope angle than upper slope angle	n/a
rectilinear	steep with equal upper and lower slope angles	n/a
volume	product of scar length, scar width and scar depth, unless otherwise other estimate given	cubic metres
		continued overleaf...

Database field	Description	Units
Material characteristics		
bulk density	bulk density of basal unit, as wet and dry bulk density, or as given	t m^{-3}
moisture content	field moisture content, in %	%
strength (cohesion)	cohesion intercept in Mohr-Coulomb equation, derived from geotechnical testing	kN m^{-2}
strength (A.O.I.F.)	angle of internal friction in Mohr-Coulomb equation, derived from geotechnical testing	degrees
strat.(acrotelm)	description of peat above permanent water table, as combinations of 'fibrous', 'humified' and 'amorphous'	n/a
strat.(acrotelm)	description of permanently waterlogged peat, as combinations of 'fibrous', 'humified' and 'amorphous'	n/a
strat.(basal)	description of layer immediately overlying failure plane, as above, or in textural composition	n/a
strat.(substrate)	description of layer immediately underlying failure plane, as above or in textural composition	n/a
above	failure plane located within the peat mass	n/a
at interface	failure plane located at the interface between the peat mass and substrate	n/a
below	failure plane located within the mineral substrate	n/a
Post-failure development		
duration	period elapsed between recovery survey and event	n/a
soil development	physical, chemical or biological departure from substrate conditions immediately post failure	n/a
ponding	long term standing water bodies, associated with impeded site drainage	n/a
peat restabilisation	development of vegetative cover over former bare peat floes, or scar sidewalls	n/a
dominant species 1	primary dominant species type by areal coverage within scar area	n/a
dominant species 2	second most dominant species type by areal coverage within scar area	n/a
dominant species 3	third most dominant species type by areal coverage within scar area	n/a
drainage/dissection	evidence of the development of sheet erosion, rill erosion or gully erosion within scar area	n/a
grazing	evidence of grazing activity within scar area	n/a
burning	evidence of burning within or in the vicinity of the scar area	n/a
secondary failures	collapse of scar side-walls by slumping or toppling, and reactivation of unstable scar margins	n/a

Appendix 2. Glossary of engineering terminology used in the study of material strength (after Vickers, 1983; Head 19862 Selby, 1993)

Term	Description
(Peak) shear strength	the maximum shear resistance which a soil can offer under defined conditions of effective pressure and drainage
Residual shear strength	the shear resistance which a soil can maintain when subjected to a large shear displacement after the peak strength has been mobilised
Undrained shear strength	the shear strength of a soil under undrained conditions, i.e. immediately after the application of stress and before drainage of water can take place
Drained shear strength	the shear strength of a soil under drained conditions, i.e. in which displacement is slow enough to permit drainage without increased pore water pressure during shearing
Failure	the point at which continued shear deformation under a constant or decreasing shear stress begins
Angle of internal friction	maximum slope angle under which a soil is stable under given drainage and loading conditions
Cohesion	internal (electrostatic) forces holding soil particles together in a solid mass
Consistency limits	the soil moisture contents at which soil behaviour changes from solid to plastic to liquid
Liquid limit	the moisture content above which soil exhibits liquid behaviour
Plastic limit	the moisture content above which soil exhibits plastic behaviour
(Shear) stress	intensity of force, i.e. force per unit area
Strain	horizontal displacement of one portion of a specimen relative to the other in direct shear tests
Strain rate	rate of applied horizontal displacement of one portion of a specimen relative to the other in direct shear tests

bracketed words denote common variation in usage

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